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GPS Tides: A Project to Determine Tidal Datums with the Global Positioning System

Stephen R. DeLoach

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U.S. Army Corps of Engineers
Topographic Engineering Center
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The recent development of On-The-Fly ambiguity resolution techniques with Global Positioning System (GPS) observations has created a powerful tool for the study of dynamic time series, such as tidal analysis or the study of water level heights. For this project a GPS receiver was successfully operated on board a Canadian Coast Guard navigation buoy. Ten days of data, at a one-second sampling interval, were collected at a station in the open waters of the Bay of Fundy, followed by ten days from an inshore mooring. The buoy data were transmitted in real time to a reference station on shore where antenna heights were computed in real time. Subsequent processing reduced the 1-Hz antenna height series to a 15-minute water surface height series for comparison to two nearby "conventional" gauges. These were the Saint John Harbour permanent gauge and a temporary Socomar pressure gauge. Mean tide heights computed from the inshore data are all within 1 centimeter. The means, computed from the inshore series, differed by 20 centimeters between the buoy and the "conventional gauges," indicating a differential slope between the water surface and the ellipsoid.

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In addition to the water surface measurements, about 20 days of GPS data was collected from a static baseline to characterize the performance of the On-The-Fly GPS system, without the influence of a moving platform. From the 20 days of data, 97 percent is within 3 cm of truth, while the mean daily heights are about 0.3 cm below the truth.

This project has demonstrated that the "GPS buoy" is a viable method of tidal datum determination and it should be possible to use the ellipsoid as the basis for water surface datums.

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PREFACE

This report is in support of the U.S. Army Corps of Engineers Civil Works Surveying and Mapping Research Program, Work Unit 32998, "Water Levels with DGPS." The work was performed during the period October 1993 to May 1995, and is in partial fulfillment of the requirements for the degree of Master of Engineering in the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada. This research was supervised by Dr. David E. Wells, University of New Brunswick, and funding was provided by the U.S./Canada Hydrographic Commission, the U.S. Army Corps of Engineers, and the Natural Sciences and Engineering Research Council of Canada, in the form of an Operating Grant, "Integration of Hydrographic Systems."

Mr. Peter J. Cervarich was Chief of the Surveying Division and Mr. Regis J. Orsinger was Director of the Geographic Information Laboratory during this project. Mr. Walter E. Boge was Director, and Colonel Richard G. Johnson was Commander and Deputy Director of the U.S. Army Topographic Engineering Center at the time of publication.

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This project would not have been possible without the collaboration and technical assistance provided by a number of individuals from the Saint John Base of the Canadian Coast Guard, the capable crew of the Canadian Coast Guard *Provo Wallis*, the Canadian Hydrographic Service, the U.S. National Oceanic and Atmospheric Administration, the U.S. Army Corps of Engineers and the University of New Brunswick.

GPS TIDES: A PROJECT TO DETERMINE TIDAL DATUMS WITH THE GLOBAL POSITIONING SYSTEM

1. INTRODUCTION

This report describes an innovative approach to establishing a tidal datum in the Bay of Fundy, near Saint John, New Brunswick, Canada. The ultimate goal of the project was to develop a new system to determine tidal datums. A secondary benefit was the potential to describe the water surface as a sloping surface, with both spatial and temporal variations. The project was also intended to introduce the technique to those federal agencies in Canada and the United States responsible for tidal datum determination, in the hope that they would be able to exploit Global Positioning System (GPS) technology as a viable tool for tidal and other oceanographic studies.

To benefit engineers and scientists in a practical application, this system was designed to provide the data necessary to establish a datum, and inversely to recover that datum at a future time. Therefore, the Bay of Fundy experiment considered three primary objectives. First, a datum was established at a location that hinders the use of conventional gauging techniques. Second, the ability of GPS to provide a data series sufficient for the Canadian Hydrographic Service (CHS) and National Oceanic and Atmospheric Administration (NOAA) methods of datum determination were examined by attempting to collect 30 days of data with a 1 second sampling interval. This provided a series sufficient to filter the noise from a floating buoy, and to perform a harmonic analysis to recover the tidal constituents. Third, a datum recovery was necessary to complete the project (Martin, 1994; O'Reilly, 1994).

The unique aspect of this project was that tidal data were collected with no

physical tie to a fixed object, such as a pier, wharf, or bottom mounted structure. The concept was to measure precisely, in real-time, a time series of heights of a floating buoy by placing a GPS receiver and antenna on board. The observations consisted of satellite broadcast C/A code phase, ephemeris data, and both L1 and L2 carrier signals at each of two stations, the buoy, and a reference station on shore. The resultant of the measurements was the three-dimensional vector, b_{AB}, between the two stations, known as the *baseline vector* (Hofmann-Wellenhof et al., 1993). It has a three- dimensional accuracy of about 1 cm, and was obtained at a 1 Hz frequency (Frodge et al., 1993). The position of the second station (buoy) was found with respect to the reference station on shore by (Hofmann-Wellenhof et al., 1993);

$$\begin{bmatrix} X_{buoy} \\ Y_{buoy} \\ Z_{buoy} \end{bmatrix} = \begin{bmatrix} X_{ref} \\ Y_{ref} \\ Z_{ref} \end{bmatrix} + b_{AB} \quad . \tag{1.1}$$

The positional time series was then evaluated using conventional tidal analysis techniques to assess the overall performance of the "GPS tide gauge."

A floating buoy was expected to exhibit high frequency motion that required filtering or damping. Therefore, several tools were implemented to reduce the series to a mean water surface. These included direct measuring of pitch and roll with a sensor installed on the buoy, and digital filtering.

The federal authorities responsible for tidal datum determination in Canada and the U.S. are the CHS and the NOAA, respectively. Coordination with these two agencies was maintained throughout the project, with the intent to develop a new

method of datum determination that is an acceptable alternative to existing methods. In both Canada and the U.S., the Coast Guard is charged with navigation safety and as such is responsible for the Aids to Navigation. These aids are a natural choice for the installation of GPS systems for datum determination. Therefore, for this project, active participation was maintained with the Canadian Coast Guard.

1.1 Motivation

Waterborne commerce is an important factor in the economy of the major trading nations (Britannica, 1970). Subsequently, a great demand is placed on engineers and scientists to maintain safe navigation, to provide adequate harbor and docking facilities, and to consider many environmental issues. Recent disasters, including the grounding of the Exxon Valdez oil tanker in Alaska and the Queen Elizabeth II near Boston harbor, further emphasize the requirement for accurate, up-to-date charts, safe channels, and modern navigation systems. The hydrographic survey is the basic building block for all of these activities. The U.S. Army Corps of Engineers (USACE) alone spends tens of millions of dollars annually performing hydrographic surveys in support of dredging operations (Miles, 1994). Scientific and geophysical studies which also rely on hydrographic survey technologies, often suffer from limited positioning capabilities. One example is the impact of long-term deep water waves moving onto the shore. Two to three centimeter vertical positions of a geophysical vessel, currently beyond the ability of the surveyor, would rectify the effects of these waves and improve relative gravity observations by two to three milligals (Loncarevic, 1993).

A significant aspect of the workload in hydrographic surveys is the establishment of tidal datums and the subsequent application of the datum to the survey. It is so much of a problem that both the CHS and NOAA have a number of authoritative texts on the subject (Marmer, 1951; Schureman, 1958; Swanson, 1974; Foreman, 1977; Foreman and Henry, 1979; Zetler, 1982; Forrester, 1983; Hicks, 1989) and have personnel that devote their entire livelihoods to this work.

A typical hydrographic survey requires establishing a horizontal positioning network and a vertical datum. Various systems are then used to position the vessel with respect to the horizontal and vertical references on shore (USACE, 1991b). In the past, these two reference networks and their respective systems of relative position fixing have been independent of each other. Furthermore, because of the difference in technology required for each, many agencies use two entirely different groups of workers to establish the reference system and to provide the expertise in transferring the horizontal or vertical reference to the survey vessel.

A *tidal datum* is defined as a level from which heights and depths are measured (Bowditch, 1984). Many levels can be used such as mean sea level (MSL), mean low water (MLW), or mean high water (MHW), depending on the requirements of the project. Establishing a tidal datum requires collecting a time series of data at a fixed site. The length of series varies depending on the accuracy requirements and the nature of the study requiring the datum. Many engineering projects use one to three months of data, while 19 years is required to encompass what is considered to be the longest, measurable, periodic effect of tide movement, the regression of the moon's ascending

node (Forrester, 1983). This time period is also referred to as a *Metonic cycle*, after Méton, an Athenian astronomer living in the 5th century B.C. (Hicks, 1989). The basic tidal movement is comprised of a series of oscillating waves that overlap upon each other and are accompanied by a progressive wave movement. The analysis of tides is based on the assumption that the rise and fall of the tide at any given locality can be expressed mathematically by the sum of a series of cosine functions that respond to astronomical conditions (Schureman, 1958). Each function in the series represents a tidal constituent having a range (amplitude) and time lag (phase). The length of time series determines the analysts ability to identify the individual constituents and it is a factor in the accuracy of the datum determination.

The accuracy of the tidal datum resulting from a series of observations is a function of many factors, including length of time series, gauge installation and operation, and meteorological effects. For example, meteorological effects from changing atmospheric pressure and wind set produce variations of tens of centimeters (Pond and Pickard, 1978). Another important point to note is that the tidal response of the ocean varies from place to place and cannot accurately be predicted from one locality to another (Pond and Pickard, 1978). An example of errors induced from off site tide readings is given in Figure 1.1 (USACE, 1991b). This example shows the effect of a time lag in the tidal wave between the survey site and a fixed tide staff. This error can be significant, even in areas with a very small range of a tide.

Many schemes have been used to minimize the tidal errors in a survey. They generally attempt to rely on a stable reference, such as a wharf or bottom mounted

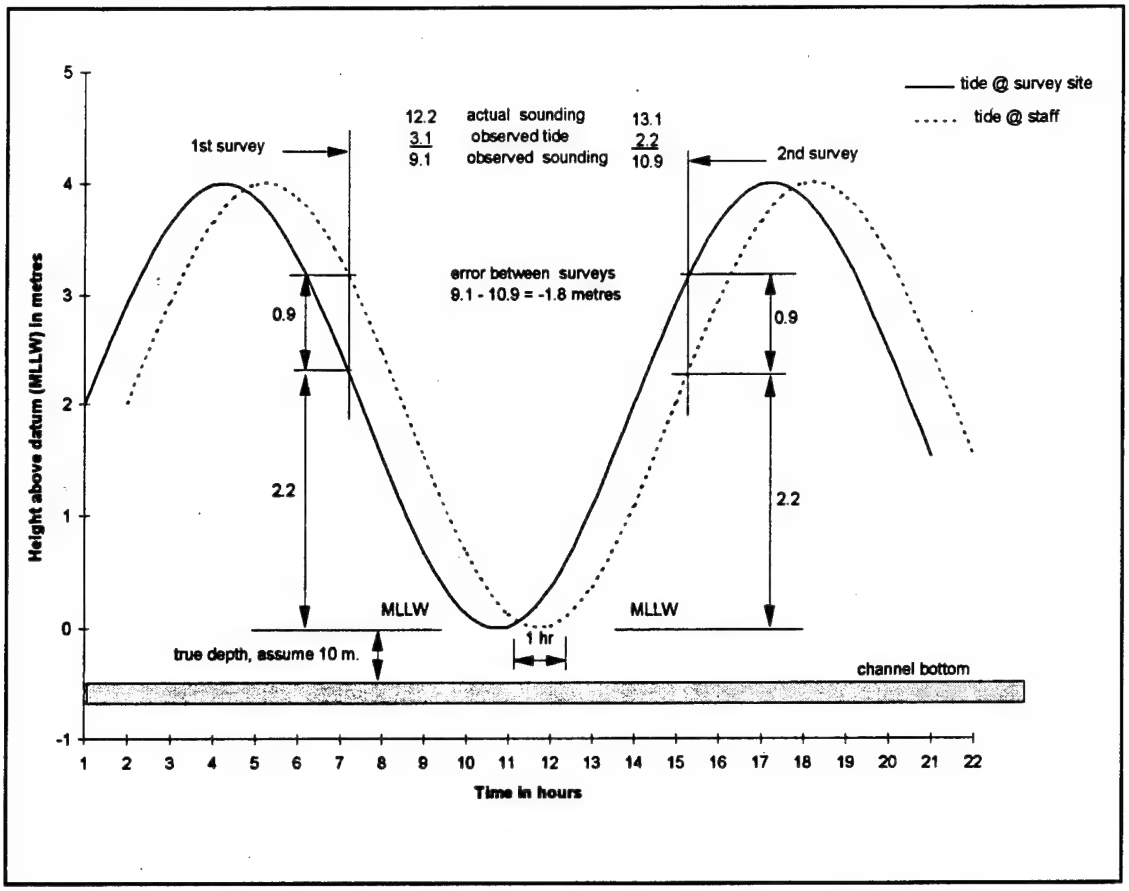

Figure 1.1 Survey error from offsite gauge reading (from USACE, 1991).

device, in the area of the survey. In the coastal environment this is often difficult and expensive. On several occasions steel pilings have been set offshore and gauges installed (USACE, 1991b). The pilings have worked well to help establish cotidal charts, but they suffer from expense and limited life.

In recent years, differential GPS (DGPS), using C/A code observations, has taken over as the horizontal positioning system of choice for hydrographic surveyors. This system has eased the burden of positioning the vessel by minimizing the number of reference stations required on shore, eliminating calibration, and extending the operational range. Typical accuracies are in the 3 to 5 m range, with newer systems

providing accuracies of 1 m (Lachapelle et al., 1993a). These accuracies are primarily a function of the C/A code range measurement accuracy of the receiver, and the rate of broadcast of the range correction to the vessel. There are many other contributing factors, such as the effect of selective availability, signal multipath and ionospheric noise, but these problems are almost completely eliminated by differential positioning techniques (Wells et al., 1986). This technique is so powerful that in the U.S. the Coast Guard and the USACE have agreed to install joint GPS reference stations throughout all maritime areas of the country (USACE, 1994). This will virtually eliminate the need to install and maintain reference stations to provide horizontal positioning of hydrographic survey vessels in the U.S.

1.2 Concept

The USACE has been able to develop a GPS-based positioning system with a unique set of capabilities (Frodge et al., 1993):

- real-time position reporting
- carrier phase measurements
- "on-the-fly" integer cycle ambiguity resolution
- 1 to 2 cm accuracies in three dimensions
- 20 km range from a stable reference station.

From a practical point of view, this new development will allow engineers and scientists to place a GPS receiver on a floating platform, measure a time series of heights relative to a fixed site (up to 20 km away), and analyze the results to establish a tidal datum at

the location of the platform. This eliminates the requirement for a stable reference at the project site. Once the platform is removed, the datum can be recovered by measuring a GPS base line from the same reference site to a vessel in the area of the original platform. A conceptual problem with this technique is the relative change in height between the reference ellipsoid (GPS basis of measurements) and the spatially varying tidal datum. The first remedy for this is to limit the GPS established datums to a "Datum Station" of geographic area that is not adversely affected by the relative height difference of the two surfaces (see Figure 1.2). This will be a site-specific determination, but generally speaking is probably a few kilometers in extent, and up to the system's operational range away from shore. A second solution, and one envisioned by the author, is to install GPS receivers on channel marker buoys along the extent of a channel. The buoys are normally only a few kilometers apart and would allow the shape of the datum to be measured, with respect to the reference ellipsoid. The geoid has not been mentioned because it does not necessarily coincide with mean sea level (MSL) (thus a

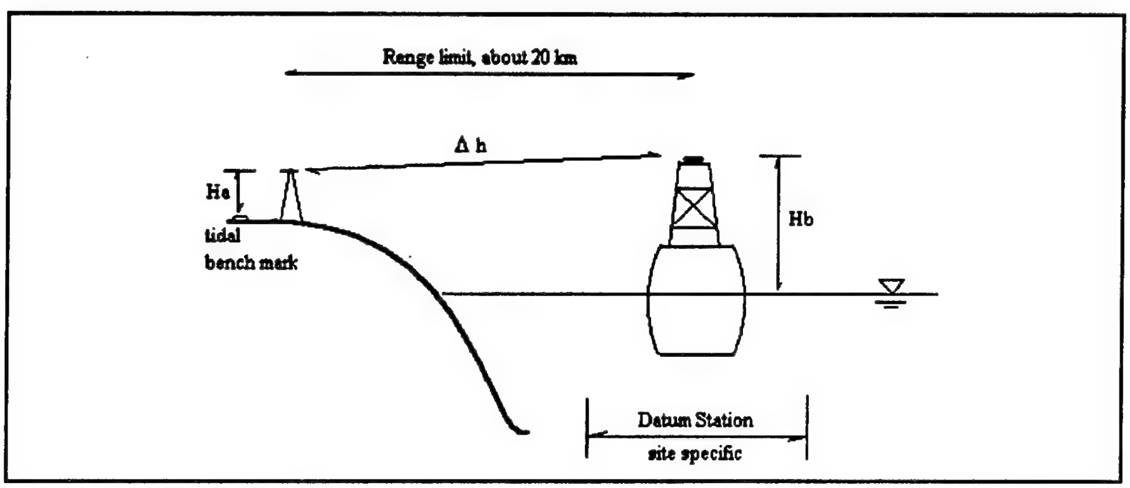

Figure 1.2 Concept of a "Datum Station."

tidal datum) at any given point (Forrester, 1983). This separation is known as *sea surface topography*, and can be in excess of 1 m (Vaníček and Krakiwsky, 1986). The difference between MSL and the geoid is created by many meteorological, oceanographic, and topographic effects. Using GPS to establish tidal datums, combined with accurate geoid models, could aid in determining these effects, and could help to provide a continuous datum "surface" from the land into the sea. Another technique is to use this technology to compute precise vertical positions of a moving survey vessel. The resulting data can then be used to create a spatial model of water surface slopes (DeLoach et al., 1994).

1.3 Implications of the Technology

A difficult and necessary component of marine science, surveying, mapping, and engineering is the precise determination of a vertical reference surface at the project site. Hardware developments for tidal data collection have generally relied on a basic assumption of a stable structure for installation. Analysis techniques, on the other hand, have advanced to allow for the analysis and prediction of tidal reference surfaces over large geographic regions. The results are dependent on the spatial relationship of the gauges and the general characteristics of the tide in that area.

Using GPS carrier phase measurements to establish tidal datums and water surface models will enable investigators to generate more accurate charts, perform better engineering design and analysis for offshore construction projects, and study phenomena on a larger scale than ever before. In addition to increased accuracies, the GPS based

observations will often (but not always) be less expensive than existing methods; especially when the vessel is horizontally positioned using the same hardware.

1.4 Contributions of this Project

Earlier projects have been conducted to determine water surface heights with GPS (Leick et al., 1990; Hein et al., 1991; Rocken and Kelecy, 1992; Lachapelle et al., 1993b). In each case the study concentrated on a short series of observations. Additionally, such constraints as a ship anchored nearby to supply power or static GPS integer ambiguity resolutions from shore were also implemented to achieve success. This project was designed to collect a 1 month data series, at a 1 second span, offshore, away from any structure or separate power source. A second series was also collected inshore to provide a direct comparison to two "conventional" gauge systems.

Chapter 2 describes the concepts necessary to understand datum determination. Chapter 3 provides a detailed description of the field experiment, followed by a description of the data collection and processing in chapter 4. Chapter 5 gives an analysis of the data collected and chapter 6 contains the conclusions and recommendations.

2. CONCEPTS

The analysis of a time series of water level heights is a primary consideration in tidal datum determination. The data are typically collected with the aid of a float mounted in a stilling well to dampen the high frequency wave action, or with some form of pressure sensing device where the damping is a function of the sensor design and the natural damping of the pressure signal with depth (Forrester, 1983). In this project, the time series describing the water surface will be comprised of two components; the GPS baseline vectors, and the roll and pitch sensory data of the buoy.

2.1 Vertical Datums

The concept of a vertical datum is certainly easy enough to visualize; it is typically thought of as "mean sea level," and physically comprises a surveyor's brass tablet with a given elevation. Yet, the realization of a proper system of heights is often the most troublesome aspect of a project.

2.1.1 Land datums On land the orthometric, dynamic, or normal height systems are used to describe heights. These use the *geoid*, or *quasigeoid* in the normal height case, as the vertical datum (Vaníček and Krakiwsky, 1986). At a specific location, each of these surfaces is related by its relationship to the earth's gravity potential at that location. In height systems this is referred to as the *geopotential number*, C_i, and is defined as the negative potential difference between a point, P_i, and the geoid (Vaníček and Krakiwsky, 1986), where the units are defined by the International Association of

$$C_i = -(W_i - W_{geoid}) \qquad (2.1)$$

Geodesy as kilogal meters. In other words, the geopotential number describes the amount of work required to move vertically from one point to another. *Dynamic heights*, H^d_i, are defined as the geopotential number divided by a reference gravity for that area. They are expressed in length units and therefore make more sense to the practitioner:

$$H_i^d = \frac{C_i}{g_r} \quad . \qquad (2.2)$$

The *orthometric height*, H^o_i, of a point is the geometrical distance between that point and the geoid, measured along the plumb line. These are often the heights used in national land datums:

$$H_i^o = \int_{P_{geoid}}^{P_i} dh = \frac{C_i}{\overline{g}_i} \quad . \qquad (2.3)$$

The mean gravity cannot be measured along the plumb line, $\overline{g}_i$ (therefore orthometric heights), because of unknown mass distributions in the earth. Therefore, the concept of *normal heights* has been introduced. These are defined as:

$$H_i^n = \frac{C_i}{\overline{\gamma}_i} \quad . \qquad (2.4)$$

where $\overline{\gamma}_i$ is the mean normal gravity between the reference ellipsoid and the point, P_i

(Vaníček and Krakiwsky, 1986). Many countries use normal height systems instead of orthometric heights as the land based datum.

Although many believe the geoid and MSL are the same, it is important to note that this is simply not true (Vaníček and Krakiwsky, 1986). A more accurate statement would be to say that the geoid is an equipotential surface, and that a homogeneous body of water with no forces acting on it would conform to that equipotential surface. But we know that the oceans are not homogeneous and do respond to numerous forces. The resulting difference between the sea surface and the geoid is referred to as *sea surface topography* and can easily amount to tens of decimeters (Vaníček and Krakiwsky, 1986).

Until recently, the prevalent datum used throughout the U.S. was the National Geodetic Vertical Datum of 1929 (NGVD 29). This system used the geoid as the basic reference datum. Its zero value was set as the mean tide level (MTL) at 26 tidal stations along the coasts of the U.S. and Canada (Zilkoski et al., 1992). This system has been recently replaced by the North American Vertical Datum of 1988 (NAVD 88). NAVD 88 also uses the geoid as the reference datum; however, the zero value is set equal to a single tide station at Pointe-au-Père, near Rimouski, Québec. This single value was chosen over the MTL at all available tide stations because it was believed the errors in knowledge of sea surface topography at the tide stations would degrade the leveling data of the network, thus forcing a deviation from the geoid as the reference surface (Zilkoski, 1995).

2.1.2 Tide datums The tidal waters of the sea contain both temporal and spatial

variations; therefore, the mean water surface at a location is typically used as the datum (Bowditch, 1984). The tidal phenomenon is the periodic motion of the sea as a result of the differences in gravitational attraction of the celestial bodies, principally the moon and sun, acting on the rotating earth (Bowditch, 1984). These differences are known as the *tide generating forces*. The tidal phenomenon can be described by two distinct, yet related, characteristics: the *tide*, or vertical rise and fall of the water; and the *tidal current*, or horizontal flow. The tidal phenomenon is described by the equilibrium theory, and is governed by Newton's universal law of gravitation. Conceptually, the tide is considered to be the sum of a series of superimposed and overlapping stationary waves and a progressive wave movement (Schureman, 1958). Mathematically the height, h, of the tide at any time is written as (Forrester, 1983):

$$h(t) = \sum_{i=0}^{n} H_i \cos(E_i - g_i) + noise \quad , \tag{2.5}$$

where H_i is the amplitude of the i^{th} fundamental frequency (or *constituent*), E_i is the phase of the constituent at the Greenwich meridian, and g_i is the phase lag of the constituent behind the Greenwich phase. Generally, the highest frequencies are the semidiurnal (twice daily) constituents having a period of about 12 hours. Some shorter period constituents do exist, of 3 and 6 hours. These are largely driven by bottom friction, and are termed the shallow water constituents (Schureman, 1958). Although well understood, the theoretical tide will differ from the observed tide because of various oceanographic, topographic, and meteorological effects (Bowditch, 1984).

A *tidal datum* is defined as "a base elevation, defined in terms of a certain phase of the tide, used as a reference from which to reckon heights or depths" (Hicks, 1989). There are a number of different tidal datums depending on the phase of the tide used for the definition, such as high water, low water, and MTL. When a particular datum is used on a hydrographic chart, it is referred to as a *chart datum*. In Canadian waters, the chart datum has been selected as lower low water, large tide (LLWLT), and in U.S. waters as mean lower low water (MLLW) (Forrester, 1983). Whatever the reference surface used, the important point is that a tidal datum is local to the site where the observations were taken. The term "local" can only be defined by comparing height requirements of a particular project to the tidal effects in the project area.

The Canadian chart datum, LLWLT, is computed from a formulation using the tidal constituents obtained from a harmonic analysis of a data series, generally 2 months of observations, taken at a site. It is the tide that would be obtained by averaging the lowest predicted low water from each of 19 successive years (Forrester, 1983). If only a few days of observations are available, then simultaneous observations may be used. The use of simultaneous observations is a technique to compute the datum at a subordinate station from observations recorded simultaneously with observations taken at a second control station. On some older charts the datum may also be referred to as the lowest normal tide (LNT). This reference surface follows the guidelines of the International Hydrographic Organization, which state that chart datum "should be a plane so low that the tide will but seldom fall below it" (Forrester, 1983).

Chart datum in the U.S., MLLW, is the average of all the lower low waters of

each tidal day observed during a specific 19-year period. The period, currently 1960 to 1978, is referred to as a tidal datum *epoch* (Hicks, 1989). In the event a 19-year observational series is not available for a particular site, then simultaneous observation comparisons are used with an appropriate control station to derive the equivalent of the observed 19-year value. Typically, 3 months of observations are used; however, only a few days of observations are required for the simultaneous observation technique.

2.1.3 GPS datum Positions, or position differences, computed from GPS observations, are based on the Conventional Terrestrial coordinate system. This is a right-handed coordinate system, with its origin at the earth's center of mass, the *z* axis pointing toward the Conventional International Origin (CIO), and the *xz* plane containing the mean Greenwich Observatory (Vaníček and Krakiwsky, 1986). For most surveying applications, utilization of the GPS observations requires transformation of the conventional terrestrial coordinates into a geodetic system, as shown in equation (2.6)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}^{CT} \Rightarrow \begin{bmatrix} x \\ y \\ z \end{bmatrix}^{G} \Rightarrow \begin{bmatrix} \phi \\ \lambda \\ h \end{bmatrix}^{G} \quad . \qquad (2.6)$$

This requires a knowledge of the position and orientation of the reference ellipsoid describing the geodetic system to be used. In North America, the geodetic system often used is based on the Geodetic Reference System of 1980 (GRS 80) reference ellipsoid. The Cartesian geodetic coordinates are then transformed into curvilinear coordinates of latitude, longitude, and height (ϕ, λ, h). Pre-existing transformation functions between

tidal datums and spatially corresponding geodetic heights generally do not exist.

2.2 GPS

For positioning purposes, the GPS satellites transmit two coded signals on one or two available carrier frequencies. These are the C/A code, modulated on the L1 carrier, and the P code, modulated on the L1 and L2 carriers. During encryption by the U.S. Department of Defense, the P code is no longer available to the public (Wells et al., 1986). Techniques have been developed over the past decade that take advantage of different combinations of these signals. These techniques can be broken down into three basic categories: single receiver point positioning, two receiver differential positioning with code signals, and two receiver differential positioning with carrier signals. Generalized descriptions of the signals and their accuracies are given in Table 2.1 (USACE, 1991a; Lachapelle et al., 1993).

The realization of these techniques in practice results in a series of implementation schemes, all with different names. For tidal datum determination and

Table 2.1 The GPS signals

Signal	Wavelength	Measurement accuracy	Positional accuracy Single pt.	Positional accuracy Differential
C/A code	300 m	30 cm	100 m	1 - 2 m
P code	30 m	30 cm	15 m	1 - 2 m
L1 carrier	19 cm	1 mm	-	+ 5 mm
L2 carrier	24 cm	1 mm	-	+ 5 mm

water surface measurement, only the differential carrier based positioning techniques are used. The characteristics available from GPS that enable the system to be used for tidal datum determination are: on-the-fly ambiguity resolution, 20 km range from a stable reference point, and 1 to 2 cm accuracy in height measurement (Frodge et al., 1993). The most important characteristic is the "on-the-fly" ambiguity resolution. This is a process to compute the number, N, of complete carrier waves, λ, between the observer at station A, and the satellite, i, while the observer is constantly in motion (Seeber, 1993). The receiver itself can accurately measure the fractional part of a wave, $\Delta\lambda$, when it first acquires the signal (Wells et al., 1986). The basic equation for the distance to the satellite is then given by (Seeber, 1993);

$$\rho_A^i = \Delta\lambda + N_A^i\lambda \quad . \tag{2.7}$$

In actual practice, the ambiguity, N, between a satellite and a receiver is never known. Instead, complex double difference algorithms are used to compute the ambiguity difference between two satellites and two receivers. Considering that the carrier wavelength is about 20 cm and the satellites are about 20,000 km away, it is impossible to instantly know how many whole waves, N (or double difference $N's$), are between the receiver and the satellite without some additional information. This additional information may include tracking as many satellites as possible, measuring the full wavelength of the L1 and L2 carrier phase, and using a very accurate differential code position (Table 2.1) as the starting point. Many techniques have been introduced to resolve the ambiguities (Hoffman-Wellenhof et al., 1993). Until recently, they all

required simultaneous observations from two stationary receiver stations. The on-the-fly (OTF) technique still requires two observing stations, but one, or both, can be in motion, hence resolution *on-the-fly* (Wells and Kleusberg, 1992). With the incorporation of radio links to transmit data from the object station to the reference station, the OTF technique can compute positions in real-time.

The final result from a GPS observational campaign will be a series of time-tagged, three-dimensional position differences, or baselines, in the Conventional Terrestrial coordinate system. These differences can be added to an initial, or reference station, coordinate value and positions of an object station computed, as shown in equation (1.1). Assuming all the appropriate transformations are taken into consideration the final coordinates of the object station will be in the user specified system:

$$\begin{bmatrix}\phi_A\\ \lambda_A\\ h_A\end{bmatrix}^G \Rightarrow \begin{bmatrix}x_A\\ y_A\\ z_A\end{bmatrix}^{CT} + \begin{bmatrix}\Delta x\\ \Delta y\\ \Delta z\end{bmatrix}^{CT} = \begin{bmatrix}x_B\\ y_B\\ z_B\end{bmatrix}^{CT} \Rightarrow \begin{bmatrix}\phi_B\\ \lambda_B\\ h_B\end{bmatrix}^G \quad . \tag{2.8}$$

The height (*h*), however, is a different matter. The height difference, Δh, resulting from a GPS survey is based on the reference ellipsoid, just as the horizontal component, as illustrated in Figure 2.1, is defined as:

$$\Delta h = h_B - h_A \quad . \tag{2.9}$$

Note that the DGPS does not measure the ellipsoidal height, *h*, only the difference in

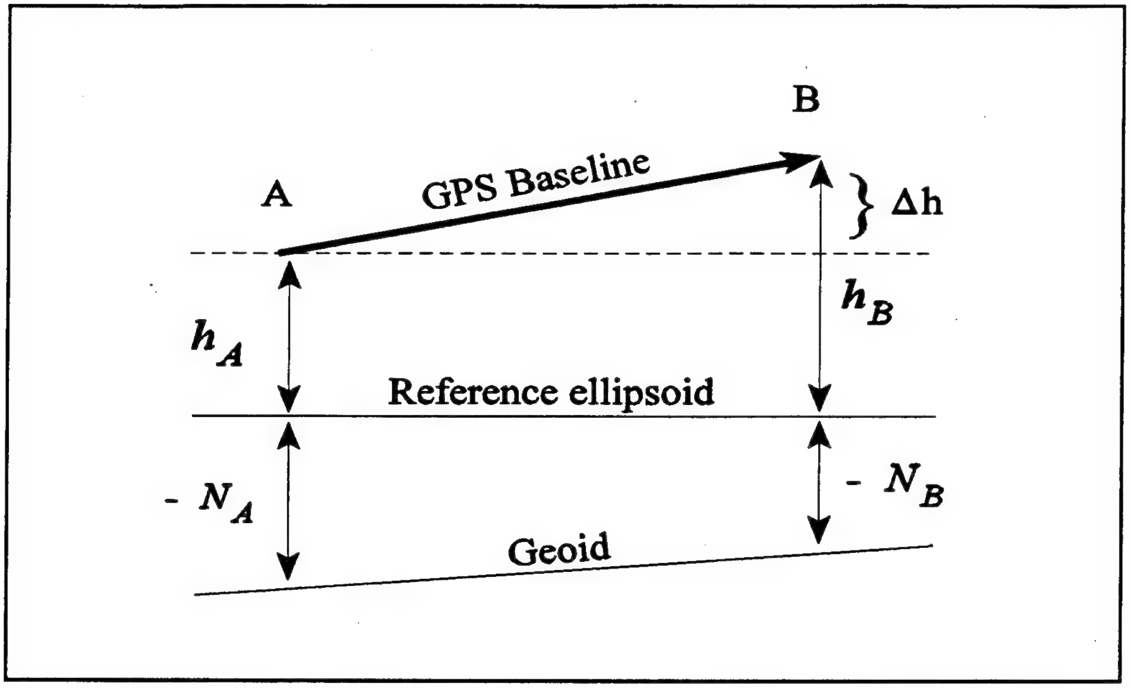

Figure 2.1 The geoid, ellipsoid and a GPS baseline.

ellipsoidal height, Δh. As previously discussed, the practitioner generally uses a system of heights referenced to the geoid. At present, we only know the absolute departure of the geoid from the reference ellipsoid, N, to an accuracy of approximately 1 m (Vaníček and Krakiwsky, 1986). It is possible to assign an orthometric height, H^o, to the GPS reference station based on the height of a known benchmark (USACE, 1991a) where;

$$H^o = h - N \quad . \qquad (2.10)$$

By doing so, an ellipsoidal height difference is used to transfer geoidal heights. From empirical analysis, the relative height difference between the geoid and ellipsoid ($\Delta N = N_B - N_A$) is known to be 5 cm over spatial separations of 25 km (Zilkoski, 1995). Therefore, geoid models can be used in a differential sense to convert GPS based ellipsoidal height differences to orthometric height differences where

$$H_B^o = \Delta h - \Delta N + H_A^o \quad . \tag{2.11}$$

2.3 Measuring Tides with GPS

For the purposes of water surface measurements, we can consider the instantaneous GPS "observable" to be the height component of the GPS baseline vector, Δh. The GPS carrier phase observables have been used to position boats or buoys by a number of investigators (Leick et al., 1990; Hein et al., 1991; Rocken and Kelecy, 1992; Frodge et al., 1993; and Lachapelle et al., 1993b). The more recent results using the improved receivers all report accuracies of 1 to 2 cm. Additionally, the sampling rate of a GPS receiver, although manufacturer dependent, is typically one second -- much faster than required for tide measurements. The carrier phase observations are generally considered instantaneous measurements and are time tagged as such. Therefore, the basic assumptions for using the GPS as a tool to collect a time series of water surface heights are:

- The measurement process will provide an ellipsoidal height difference between a reference station and a GPS receiver floating on the water's surface
- The data can be collected at a rate of 1 Hz
- The GPS component of the height difference will have an accuracy of 2 cm

By placing a GPS receiver and antenna on a buoy and anchoring it on station for a suitable time period, a time series of tide heights can be generated for analysis. The analysis will result in developing a tidal datum for that buoy station, relative to that

reference station. The instantaneous elevation of the benchmark on shore, relative to that buoy station, is given by (see also Figure 2.2);

$$H^{w}(\phi_b\ ,\ \lambda_b\ ,\ t) = H^{b}(\phi,\ \lambda,\ t) - \Delta\underset{a}{\overset{b}{h}}(t) - H^{a}(\phi,\ \lambda) \tag{2.12}$$

where H^b is the height of the antenna mounted on the buoy above the water surface after correction for pitch and roll effects, Δh is the GPS-determined ellipsoidal height difference, and H^a is the height of the reference antenna above the reference benchmark.

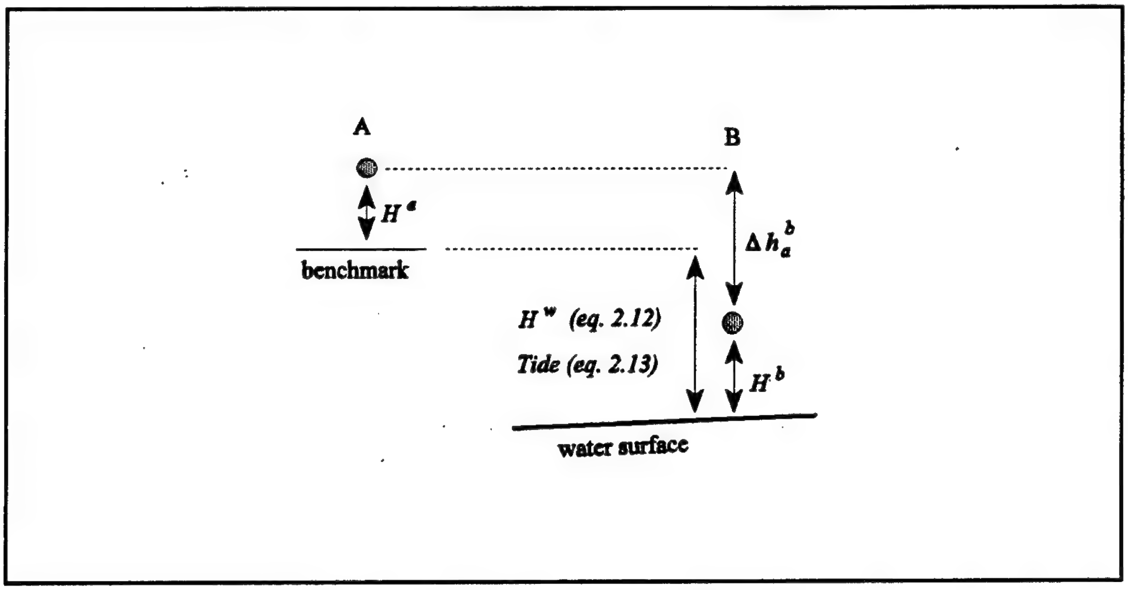

Figure 2.2 Measuring tides with GPS.

Tidal analysis (such as computation of mean values) of the time series, $H^w(\phi_b\ ,\lambda_b\ ,t)$, will provide a datum value(s), $d(\phi_b\ ,\ \lambda_b)$, on the reference benchmark, such as MLLW. At any future time, the height of the tide above, or below, the datum would be found by:

$$Tide(\phi_b,\ \lambda_b,\ t) = d(\phi_b,\ \lambda_b) + H^{a}(\phi,\ \lambda) + \Delta\underset{a}{\overset{b}{h}}(t) - H^{b}(\phi,\ \lambda,\ t) \quad . \tag{2.13}$$

Although simple in concept, there are four considerations in the above model. First, the

GPS determined height difference will be limited by the state of the art in GPS technology. Currently the accuracy is at the centimeter level, and the range between reference station and buoy is limited to 20 to 30 km (Frodge et al., 1993). Second, determining the height of the reference station antenna above a reference benchmark is the same as measuring the height of a conventional tide gauge with respect to a set of benchmarks. The GPS antenna is not the permanent artifact. Each time the datum is used, H^a must be established relative to the benchmarks by an appropriate form of leveling. Third, the height of the buoy-mounted antenna above the plane of floatation of the buoy will be constantly changing, and the actual height must be corrected for pitch and roll (assuming this motion introduces significant errors). Finally, the simple model given is valid only if the reference station and buoy locations remain constant. The temporal and spatial variations between the water's surface and the ellipsoid will introduce errors if the spatial relationship of the two ends of the GPS base line do not remain constant, or if a transformation function is not created.

2.4 Reduction to a Tidal Datum

According to equation (2.12), there are three variables to contend with in the data processing to arrive at a time series of heights for processing the tidal datum(s).

The height of the GPS antenna that is mounted on the buoy above the water surface, H^b, will be constantly changing. If these changes are considered significant, they must be corrected to provide an antenna height above the water's surface corresponding in time to the GPS sample of the satellite signals. This can be

accomplished by use of a roll and pitch sensor. The device should have a data sampling rate at least equal to the rate of the GPS data. Further, the data stream must be time correlated with the observables generated by the GPS receiver.

The ellipsoidal height difference measured by the GPS, Δh, cannot be mathematically transformed to the geoid or a tidal surface without first defining the transformation function. This function requires the measurement of a time series of heights, as in equation (2.12), and reduction to a mean value or tidal datum. Essentially, this system will be using an ellipsoidal "ruler" to measure a physical phenomenon, the tide.

The elevation of the reference GPS antenna above a benchmark, H^a, is actually the height of the antenna above a series of previously installed tidal benchmarks. Installing a tide gauge and analyzing subsequent data is an intensive endeavor, generally in support of a long term project or scientific study. Therefore, the datum values are physically referenced to a series of stable and secure benchmarks in the vicinity of the tide gauge. The respective heights of the benchmarks and GPS antenna are determined by conventional leveling techniques as prescribed by the national tidal authorities (Hicks et al., 1987; Forrester, 1983).

2.4.1 Series length and sampling interval The analysis of a time series of data requires careful consideration of the parameters and their representation in the record. Two criteria to help in the design and analysis process are the *Nyquist critical frequency* (Press et al., 1992) and the *Rayleigh criterion* (Forrester, 1983). For tidal applications

in geomatics studies, the sampling interval has, in the past, generally been 1 hour, and the record length may span from a few days to many years (Forrester, 1983). Faster sampling rates or an increased length of record may provide additional information about the measurement process, or the function being modeled, such as noise in the measurement or some unexpected frequencies in the tidal record. An example of noise may be wave induced, or current induced, errors in the height measurement. Unexpected frequencies may be caused by any number of periodic effects creating a temporary slope of the water surface, a seiche for example. To use harmonic analysis techniques effectively, the data collection must be performed in accordance with the requirements of the study.

The Nyquist critical frequency is defined as (Press et al., 1992):

$$f_c = \frac{1}{2\Delta} \tag{2.14}$$

where Δ is the sampling interval. The value of the Nyquist frequency lies in the fact that within the frequency band $-f_c < f < +f_c$ the function will be completely determined. Any frequencies outside this band will be falsely translated into the band and will appear as another frequency. This is termed *aliasing*, and is graphically shown in Figure 2.3, where h_t is the real signal, k_t is the aliased signal, and the sampling is denoted by the dots. Alternatively, if the time domain, $h(t)$, contains only frequencies within the Nyquist band, then the frequency domain, $H(f)$, will equal 0 for all $|f| > f_c$ (Press et al., 1992). Therefore, the sampling rate must be chosen small enough to record the highest frequency believed to be present or of interest. For tidal applications, sampling intervals

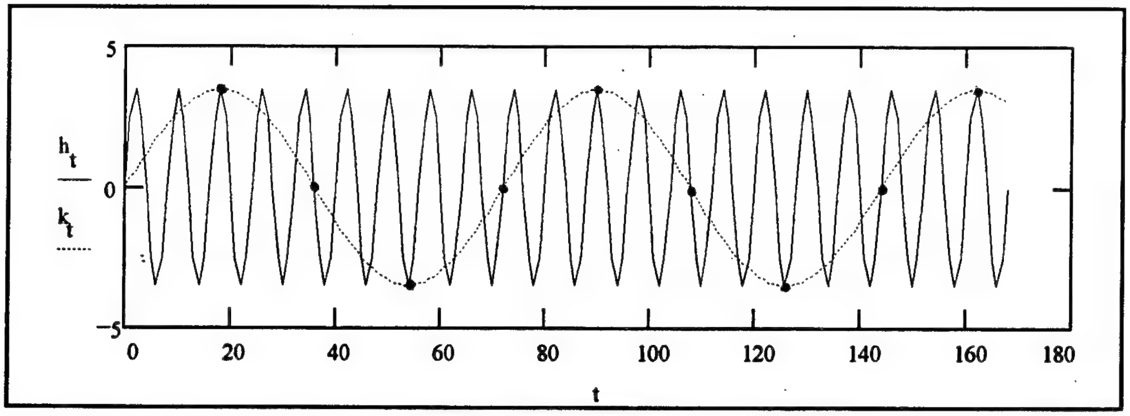

Figure 2.3 Aliasing.

of 1 hour are often used based on the assumption that the shortest periods of about 3 hours are from the shallow water constituents. Frequencies can exist in the record that have periods less than 2 hours, requiring faster sampling rates, such as a seiche or wave induced motion. Therefore, it may become advantageous to increase the sampling rate to separate these events from the measurement noise.

The Rayleigh criterion sets the minimum record length required to separate two frequencies. It is given as (Forrester, 1983):

$$T \geq \frac{2\pi}{\omega_1 - \omega_2} \quad . \tag{2.15}$$

The constituent angular speeds, ω, can be selected from a table (Schureman, 1958) to determine which tidal constituents can be uniquely identified using the Rayleigh criterion. As an example, the M_2 and N_2 lunar semidiurnal constituents would require a record length of

$T = 360° / (28.9841042\ °/hr - 28.4397295\ °/hr) = 661.3$ hours or 27.6 days,

therefore a 30-day record would separate these two constituents.

This simple example assumes the time series did not contain any noise to alias the frequency band or to appear as a frequency close to a tidal constituent. In practice, there will always be some level of measurement or process noise within the data series (Forrester, 1983). The record length required to separate pairs of the major tidal constituents, as computed by the Rayleigh criterion, is given in Appendix A.

Also, it has long been believed that hourly tide heights are sufficient to serve as the time domain for transformation into the frequency domain to identify the shortest period constituents present (Schureman, 1958). Therefore, the task of preparing a data series to serve as the time domain representation of the real process was to collect a data set in the field at some sampling interval, and to extract the hourly samples that properly depict the tide phenomenon. Alternatively, all of the GPS data could be used (versus extraction of hourly heights) to learn more about the buoy motion or other noise present in the tidal record.

For sensors that feel the direct effect of wave action, such as a floating GPS receiver, the sampling interval would have to be very short to help filter the induced motions (or help identify the frequencies of the motion). The tidal constituents would then be derived from a filtered data set, or the entire series analyzed to define all of the frequencies present, including buoy motion. Sensors incorporating the old standby float-counterweight are mechanically damped, and the sampling interval could be lengthened accordingly. The older style analog records can be manually filtered to select the hourly height series for analysis (Godin, 1972).

2.4.2 Tidal analysis Combining the observations of the GPS baselines, buoy dynamics, and spirit leveling will result in the time series of heights, H^w, as shown in equation (2.12). To ensure that no aliasing occurs on this project (folding of frequencies above the Nyquist frequency), the sampling interval was 1 second, much shorter than required to model the tidal frequencies. The time series was then filtered, with a mean running average, to obtain the series to pass to the tidal analysis phase of the project. The intent was to eliminate all process noise and produce a data series suitable for tidal analysis. The process noise was composed of buoy motion at nontidal frequencies and data spikes from observational problems. The nontidal frequency motion of the buoy was caused by a variety of environmental sources, including wave action, currents creating a tilt, or variations in the buoy's plane of floatation from changing water density.

The mean running average filter was used to generate a 15 minute (CHS standard) data series from the 1 second series provided by the GPS system. This is only to accommodate the tidal datum computational routines currently in use by the tidal authorities. With the computing power available today, it is possible that, in the near future, the entire 1 second series could be used in the tidal analysis phase. Thus, shorter period events could be examined that are now lumped into the "noise" category.

3. AN EXPERIMENT FOR THE BAY OF FUNDY

The primary goal of this project was to develop a new system for the determination of tidal datums. It was also intended to introduce the technique to the federal agencies in Canada and the U.S. that are responsible for tidal datum determination, in the hope that they would be able to exploit GPS technology as a viable tool for tidal and other oceanographic studies.

For a practical application, this system was designed to provide the data necessary to establish a datum, and inversely to recover that datum at a future time. To evaluate the feasibility of using GPS for tidal studies, an experiment was conducted in the Bay of Fundy, New Brunswick, Canada. This experiment considered three goals. The first goal was to establish a datum at a location that hinders the use of conventional gauging techniques. The second goal was to examine the ability of the GPS to provide a data series sufficient for the CHS and NOAA methods of datum determination by attempting to collect 30 days of data with a 1 second sampling interval. This would provide a series sufficient to filter the noise from a floating buoy, and to perform a harmonic analysis to recover the tidal constituents. Finally, a datum recovery was conducted to complete the project (Martin, 1994; O'Reilly, 994).

3.1 Site Selection

The location chosen for this study was Saint John Harbour, New Brunswick. It is located at the mouth of the Saint John River, midway along the north shore of the Bay of Fundy. The river widens into the Bay of Saint John, which extends approximately 8-

km to the line between Cape Spencer and Lorneville. The sea bed gradually rises from a depth of 30 m at the seaward edge to zero meters at the beach of Courtenay Bay (Neu, 1960). The harbor area is protected from the open sea by Partridge Island and two breakwaters (see Figure 3.1). Just above the harbor, the river narrows in a rocky gorge known as the "Reversing Falls." Within this gorge, in a distance of several hundred meters, the 8 m Bay of Fundy tide range drops to approximately 1 m in the lower Saint John River. Although Saint John Bay is largely saline, during the freshet the river flow dominates and a fresh water wedge extends to the interface with the larger Bay of Fundy (Neu, 1960). On most years the freshet seems to peak in late April and early May with more typical flows by June.

3.1.1 Reference gauges The CHS has a permanent tide station located in the harbor, adjacent to the Saint John base of the Canadian Coast Guard (CCG), that has been in operation for many decades (O'Reilly, 1994). This station serves as a reference port for the prediction and publication of the Canadian tide tables (Canada Department of Fisheries and Oceans, 1992). The gauge is located inside the Pugsley Terminal warehouse, approximately 200 m downstream of the CCG station. It is a mechanical float/counter weight design mounted in a 1 m diameter stilling well (McGinn, 1994). The well is built inside the structure of the wharf and is connected to the open water by a 0.1 m orifice. The gauge is connected to a Tidal Acquisition and Telemetry System (TATS) digital data recorder that logs heights every 15 minutes. It is set to Atlantic Standard Time (AST). Data from this gauge were collected by a telephone connection

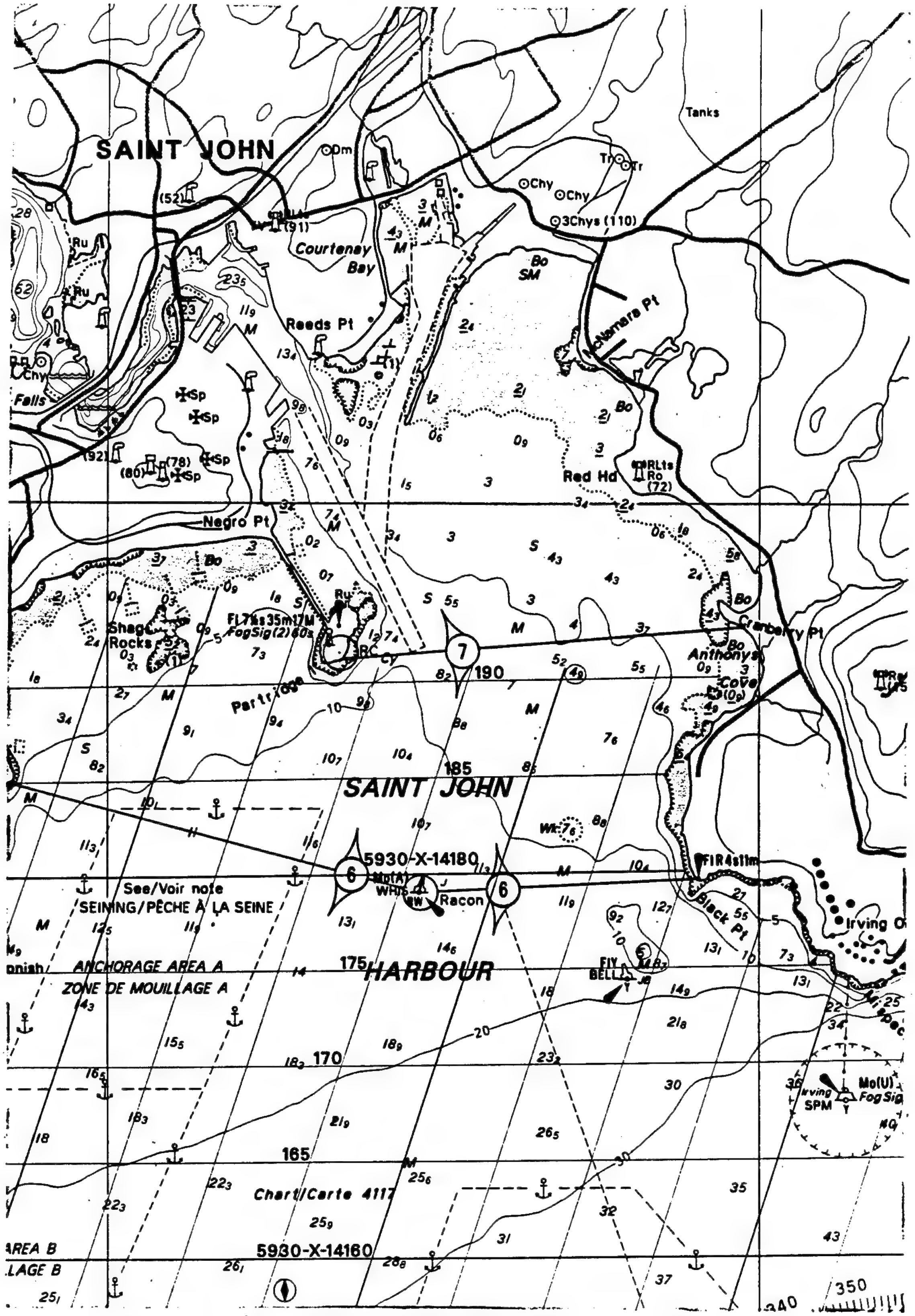

Figure 3.1 Saint John Harbour (from Canadian Coast Chart LC 4116).

to the gauge, and using a personal computer (PC) with a MODEM, data were downloaded every few days.

The CHS permanent tide station and the CCG facility are located in the downtown area of Saint John on the Saint John River. In direct support of this project, CHS established a Socomar TMS 1000 pressure sensing tide gauge and a staff gauge as well as performed the precise levels to vertically reference all gauges to a single datum (Lewis, 1993). The Socomar gauge, installed by CHS at the east end of the south slip of the CCG base in Saint John, serves as a redundant ground truth for accuracy computations. This gauge uses a pressure sensing device corrected for water density (at the sensor) and is set to log data in Universal Coordinated Time (UTC). The data were downloaded every few days by direct RS 232 connection between a notebook computer and the gauge.

A tide staff, graduated in decimeters, was installed by the CHS on the north face of the south slip at the CCG base. Zero of the staff was set to the CHS chart datum for Saint John Harbour. Staff readings were taken randomly during the project as a check on each of the automated systems. Tide staff readings were taken in the UTC system.

The Saint John Coast Guard Base provided the buoy and made all necessary modifications to the buoy to mount the GPS system, installed the appropriate power supply, and installed and removed the buoy (Hope, 1994).

3.2 Project Overview

Project planning began in September 1993, with the commencement of the

University of New Brunswick (UNB) winter term. A preliminary meeting took place at the Bedford Institute, Dartmouth, Nova Scotia, Canada, on 29 October 1993, to discuss the project with those agencies that had an interest in the GPS technology and the GPS tides concept. Those in attendance were the CHS, Department of Public Works Canada, the CCG, and UNB (see Appendix B). The project was also discussed during subsequent telephone calls with the USACE and the NOAA (Martin, 1994). Each organization, in turn, agreed to participate in the project at various levels, according to their particular interest.

The field portion of the GPS tides project began on 24 May 1994, when each of the parties mobilized to Saint John, New Brunswick, to perform their respective installation tasks. Final modifications to the buoy required 2 weeks, (1 week longer than anticipated). Fortunately, this "extra" time created an opportunity to troubleshoot the equipment installation on the buoy equipment housing. The OTF system operated continuously during this week, and exhibited random system failure. The GPS receiver located in the equipment housing was generating code pseudoranges with extremely large errors. This, in turn, caused the OTF software to fail. This problem was created by the VHF radio antenna cable that was inside the housing, near the GPS receiver. This problem was remedied by insulating the antenna cable with a nonferrous material, aluminum foil. No other problems occurred during the installation phase and the overall project schedule is given in Table 3.1.

In total, three "conventional" gauge systems and two OTF GPS systems were installed and operated during this project. The conventional gauges included the CHS

Table 3.1 Schedule.

All parties mobilized to Saint John includes:		24 May
CHS	installation of Socomar gauge and 9-meter staff in south slip of CCG base, and levels to all gauges	
CCG	buoy readiness and installation, shop fabrication of antenna mounts, power supplies, carpenter fabrication of equipment housing/installation	
NOAA	overall assistance and project guidance	
USACE	all GPS and computer equipment and installation support	
UNB	project coordination and installation support	
Begin data collection in boat slip at CCG base		8 June
Begin offshore data collection		9 June
Return to CCG base and begin inshore data collection		14 July
End data collection and disassemble all equipment		24 July

permanent gauge located a few hundred meters down river of the CCG base, a Socomar pressure sensing gauge set in the CCG's south slip, and a 9 m tide staff set near the Socomar gauge. The GPS systems included the system mounted on the buoy, and a second system rigidly mounted on the roof of the CCG building (see Figure 3.2). Therefore, three GPS receivers were operating; one reference station, a "rover" on the buoy, and a static "rover" on the roof. The reference station was also mounted on the roof, adjacent to the static "rover." As a result, four independent measurements of the tide were being made along with a series of GPS positions of a static point.

The objective of the field activities was to collect three GPS based data sets,

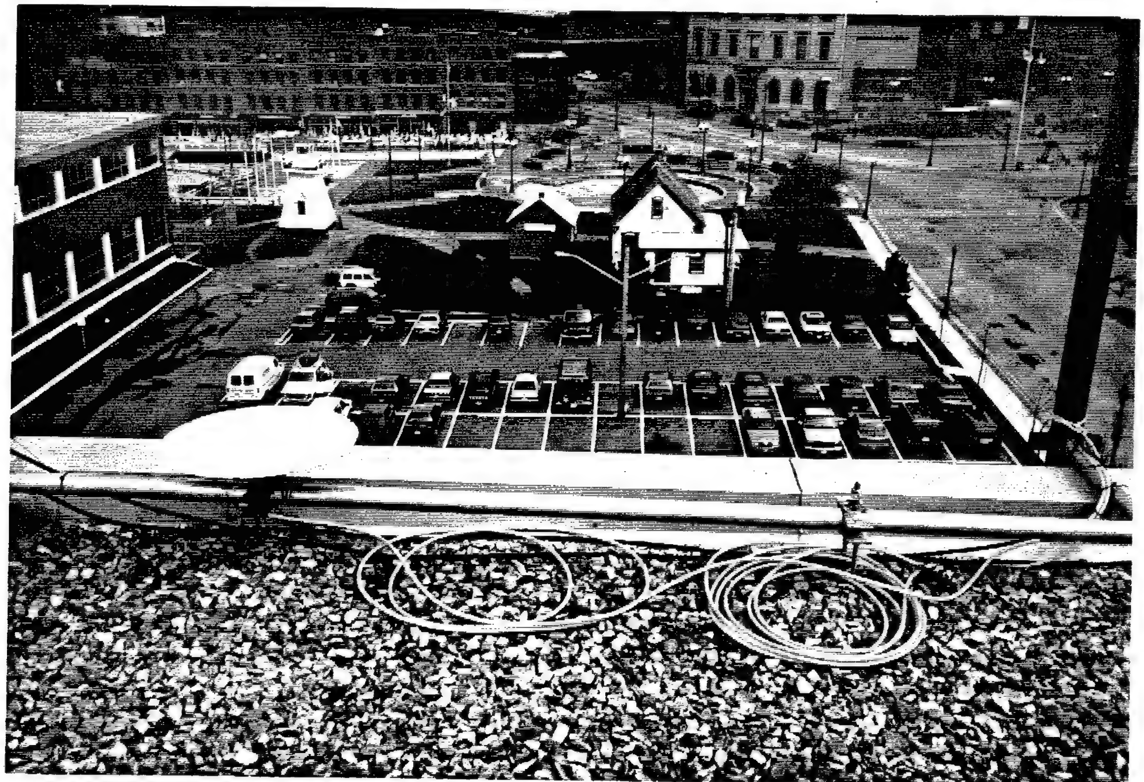

Figure 3.2 A photograph of the reference GPS antenna and the second antenna mount (antenna removed to show the mounting system).

along with simultaneous data from the permanent CHS float gauge and the temporary pressure gauge. The three GPS data sets were: (1) heights of the static "rover" mounted next to the reference station on the roof, (2) approximately 10 days of heights from the buoy while it was moored in the river, adjacent to the conventional gauges, and (3) one month of height data from the buoy moored offshore. A month long series is considered to be the minimum length for a satisfactory development of the more important tidal constituents (Schureman, 1958; also Appendix A).

The GPS buoy, which was moored in the river adjacent to the conventional gauges, collected data for two purposes. First, the GPS was set to the local CHS chart datum and the tide tracked to demonstrate a datum recovery. Second, these data were

directly compared to the Socomar pressure gauge established in the boat slip and the permanent float gauge to examine the system accuracies. The purpose of the offshore data series was to demonstrate the technology in a real world situation, where conventional techniques are not possible.

Table 3.2 lists the major equipment required for the successful execution of this project. This list is subdivided into three categories: the buoy, the reference station, and ancillary support. The buoy category contains all the equipment that was installed on the buoy. Likewise, the reference station contains all the components required to operate the GPS reference station. Ancillary support equipment was used to provide ground truth and level ties for the GPS system.

Table 3.2 Equipment.

Item	quantity	Item	quantity
Buoy		Reference station	
350 amp hour batteries	24	OTF GPS software	1
tide staff	4	GPS receiver with office module	2
equipment housing	1	notebook computer with docking station	2
GPS receiver	1	radio receiver	2
notebook computer with docking station	1	external Bernouli drive	1
pitch/roll/heave sensor	1	computer with Gb disk	1
radio transmitter	1	magneto optical drive	1
volt meter	1	GPS antenna mount	2
GPS antenna mount	1	radio antenna mount	2
radio antenna mount	1		
Ancillary support			
9 meter tide staff	1		
automatic tide gauge	1		
precise level w/ rods	1		
total station	1		
target/prism set	3		
GPS processing sw	1		

3.3 Spirit Level Ties

Each of the gauges was vertically referenced to a single datum, the CHS chart datum. This was accomplished in two phases: spirit levels, and reciprocal vertical angles. The spirit levels were used to tie CHS tidal benchmarks to the permanent float gauge and to the Socomar pressure gauge and tide staff located in the CCG slip. These were run by the CHS with assistance from the NOAA. Table 3.3 gives a list of the primary elevations for this project.

Table 3.3 GPS Tides, project heights.

Mark or Value	Elevation (meters)
Secondary GPS antenna	31.025
Primary GPS antenna	31.003
TBM Clamp	30.838
TBM Drain	30.806
TS 2 1958	11.894
TBM Pin	9.719
TBM Bolt	9.680
Top of 9 meter staff	9.002
MSL (1960-1978)	4.406

The primary tidal benchmark for this project was the CHS mark, TS 2 1958. Two temporary bench marks, TBM Pin and TBM Bolt, were also installed in the top of the wharf at the west end of the CCG boat slip. To establish chart datum on the GPS reference station, the elevations had to be transferred from the wharf to the roof of the CCG building, about 20 m in height. The equipment for this task was provided by the UNB, and a team consisting of personnel from the UNB and the USACE accomplished

the work. Two independent surveys were performed with a total difference of 5 mm. However, the team performing the work believed the second survey used more accurate equipment and better procedures, and based on their recommendation the elevations from the second survey were used. The vertical angles were performed first with a Wild TC 500 and second with a Wild TC 2002, the TC 2002 being more accurate. In addition, the second survey took advantage of tools used for mensuration of industrial equipment to minimize the errors of transferring from the theodolite to a spirit level. This final step used a Wild NA 3000 precise level to establish elevations of several points on the roof, including the two antenna mounts and two temporary benchmarks, "Clamp" and "Drain." A 19-year MSL value was also computed by Mr. Doug Martin, NOAA, from a set of values provided by the CHS, Ottawa.

3.4 The GPS

Although many differential GPS processing techniques could be used for this project, only the OTF GPS positioning approach was considered feasible, in a practical sense. All techniques, except OTF, require a period of static initialization (Wells and Kleusberg, 1992), making them impractical for a GPS tides system. Water surface measurements have been demonstrated by several groups using OTF techniques (Hein et al., 1991; Rocken and Kelecy, 1992; Frodge et al., 1993; and Lachapelle et al., 1993b). The GPS hardware and software used for this project was donated by the U.S. Army Topographic Engineering Center to support their activities in the USACE Surveying and Mapping Research Program.

OTF positioning can be performed with C/A code L1 frequency GPS receivers (Remondi, 1993). During their studies and design process the USACE determined what they considered to be the best solution for a practical system operating in support of dredging and hydrographic surveying. This required a newer vintage receiver with C/A code noise of 0.2 to 0.3 m, and full wavelength L1 and L2 carrier frequencies, even under P code encryption (Remondi, 1993). Today there are several receivers on the market that meet these requirements, including Allen Osborne, Ashtech, Trimble, and Lieca. For their system the USACE chose the Trimble Model 4000SSE (Frodge et al., 1993). Therefore, that is the hardware that was used on this project.

As with the hardware, there were several options for the software to be used for the GPS tides project. Institutions, or individuals, believed by the author to have an OTF capability are listed in Table 3.4. Aside from proven field performance, the major distinction in software was the ability to process in real-time by use of a radio link. Real-time processing was desired for the tidal project to eliminate the need to store enormous amounts of data on board a buoy, or to visit the buoy daily to download the data. Proven field performance was, of course, a precursor to transition from a GPS research project to the tides research project. The GPS software was also donated by the USACE.

The USACE system produces three types of output files: differential code positions, differential carrier positions, and the raw receiver files (Barker, 1994). The latter two were of interest to this project. In reality, only the differential carrier positions were necessary. However, the raw receiver data was also stored to aid in examining the

overall GPS performance. The raw data is in a binary format, requiring sophisticated programming to archive and/or extract specific files; therefore, the data sets were manually broken once a day to minimize file size. The result was the requirement to process an entire day's data to examine, in post processing, the GPS performance. The differential carrier positions, computed in real-time, are output in an ASCII string. This includes latitude, longitude, height, and time. The raw receiver data and the carrier positions were logged to their own directories on a magneto-optical disk drive. These drives have the capability to store 1 Gb on a single disk, producing a relatively inexpensive medium for data archiving.

Table 3.4 OTF Capability.

US Department of Commerce National Geodetic Survey
US Army Corps of Engineers
University FAF Munich
University of Calgary
Ohio State University
John E. Chance and Associates
Allen Osborne, Inc.
Ashtech, Inc.
Leica, Inc.
Trimble Navigation, Ltd.

3.5 Roll, Pitch and Heave Sensor

Correcting the antenna height above the water's surface requires measuring the pitch and roll of the buoy. Furthermore, this data must be time correlated to the GPS data. The device chosen for these measurements was a TSS 335B Roll, Pitch and Heave sensor. This unit utilizes five accelerometers to sense motion and is designed to operate on small marine vessels. It measures pitch and roll with an accuracy of about 0.1° and heave to about 5 cm (TSS). The error in height of the antenna above the water's surface is estimated to be 5 mm up to a roll angle of 40°. This approximation is computed by:

$$\Delta h = (d\ \cos(\beta + \alpha) - d\ \cos(\beta)) - 1 \qquad (3.1)$$

where d is the length of the lever arm, β is the nominal tilt, and α is the accuracy of the tilt measurement.

Roll, pitch and heave measurements received directly from the sensor were time matched with the GPS data. This was performed by storing each TSS data packet as it was received by the computer, at a rate of 85.33 Hz. A GPS position was received once per second, with a 300 ms delay from the actual observation at the antenna. Upon receipt of the GPS position, the corresponding TSS data packet (300 ms in the past) was selected and added to the GPS position data string for transmission via radio back to the reference station on shore. Finally, the roll and pitch was translated into a change in height of the GPS antenna with respect to the water's surface.

The pitch and roll sensor used on this project was relatively expensive (equal in price to all of the other electronics combined), and it was a significant power drain on the batteries. Therefore, consideration would normally be given to selecting a pitch and roll sensor that delivered the required accuracy at minimum cost and power consumption. Using equation (3.1), the height error (effect on height of the antenna above the water's surface) versus tilt measurement accuracy was computed for several lever arm lengths. The results are plotted in Figure 3.3, which serves as a guide for selecting a pitch and roll sensor to meet the requirements of a project.

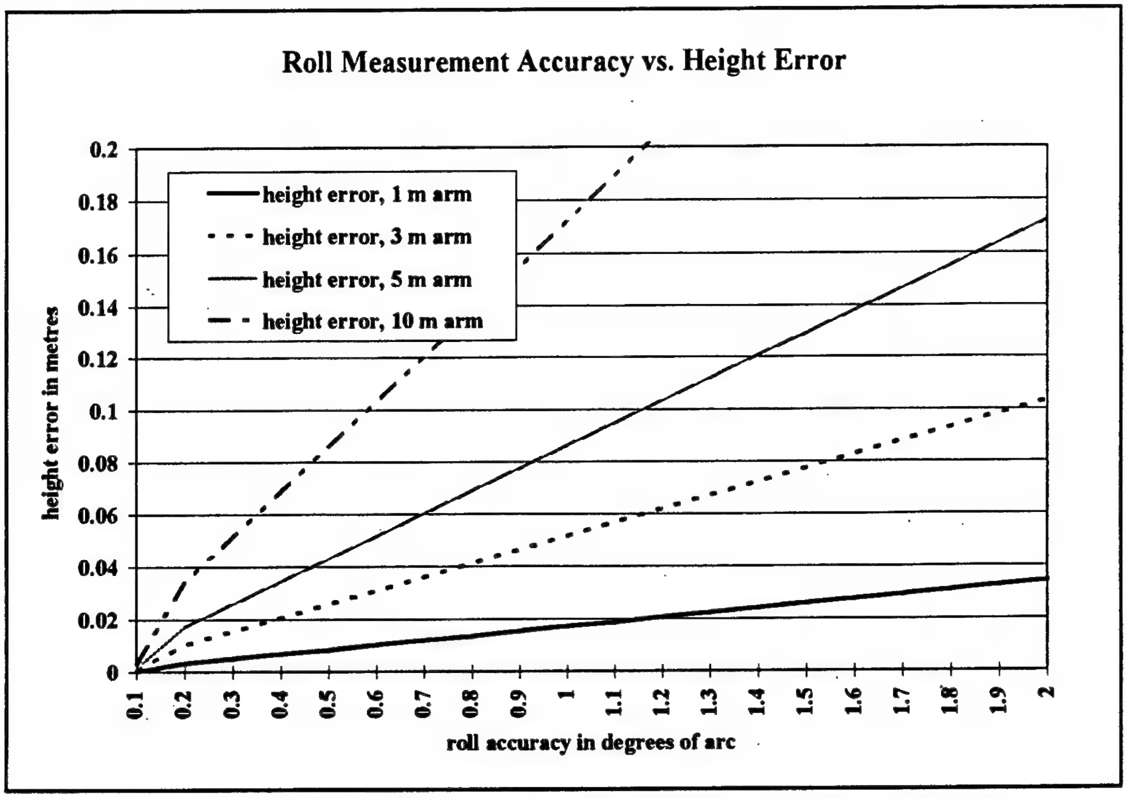

Figure 3.3 Error in antenna height versus roll measurement accuracy for several lengths of lever arm.

3.6 The Radio Link

Transmitting the GPS (and roll and pitch) data from the buoy to the reference station required a data link capable of transmitting at a rate of 4800 baud (Frodge et al., 1993). This was a much higher data rate than is typically used for real-time differential GPS positioning systems in marine applications. Most systems used for marine positioning have relied on the C/A code pseudoranges and differential corrections where the required data rate is 50 baud (Radio Technical Commission for Maritime Services (RTCM), 1993). Standard message structures for the differential code data have existed

for some time, enabling the users to maintain some independence in GPS receiver selection and to use broadcast corrections from another source. This standardized message structure has recently been expanded to include the carrier phase based, OTF techniques (RTCM, 1993). The USACE system has been designed to work with one of two radio systems shown in Table 3.5.

Table 3.5 Radio specifications.

	Unit # 1	Unit # 2
Manufacturer	Trimble Navigation, Ltd.	Repco, Inc.
Model	Trim Talk-900	SLQ - 96
Transmit Power	1 watt	4 watts
Frequency range	902 to 928 MHz	138 to 174 MHz
Modulation	spread spectrum	16K0F1D
Type acceptance	FCC # JUP-4010-900	ABP959BB5043-4
Operating frequency	906, 909, 912, 915, 918, 921, 924 MHz	163.0, 164.5 MHz

A significant complication in using a real-time differential GPS system is the authorization process to broadcast the differential data. The administrative process for each country is different, and the proper authorities must be contacted. Simply determining who these authorities are can be cumbersome. This subject is also within the domain of frequency allocations that may already be authorized to a federal agency, and these agencies must confer within their own chain of command for such issues. Spectrum Management of Industry Canada, located in Saint John, New Brunswick (Savoie, 1994), provided approval for the radio link frequencies used for this project.

On 25 May 1994, the work boat *Lorrie Susan* was used to transport a complete, operational, OTF system to the intended offshore buoy location, near the disposal

grounds at the outer edge of Saint John Harbour. Installation on the *Lorrie Susan* took approximately 1 hour. The purpose of this trip was to test the VHF radio system in the location and configuration that would be used on the buoy. The VHF radio broadcast power was 4 W. This was not powerful enough for the transmission to reach from the buoy location to the reference station because of obstructions in the city. Therefore, an alternative buoy location was chosen. This location, on the southern side of Partridge Island, had a clear line of sight to the reference station on the roof of the CCG administration building, and there was no problem with the radio reception. The new location was in the same type of ocean environment as the original, and the CCG approved the location as not obstructing vessel traffic.

3.7 Computer Requirements

The USACE OTF system is operated automatically with a 486 MS DOS based PC located with each GPS receiver. The current configuration uses a notebook style computer (Frodge et al., 1993). Data logging is directed to any user defined drive, allowing use of an external device, for long period operations (Barker, 1994).

3.8 Buoy Considerations

Following a series of discussions with the CCG, a 2.9 m whistle buoy was selected as the platform for the GPS equipment (Figure 3.4). The Saint John base had one available that they outfitted and dedicated to the project (Hope, 1994).

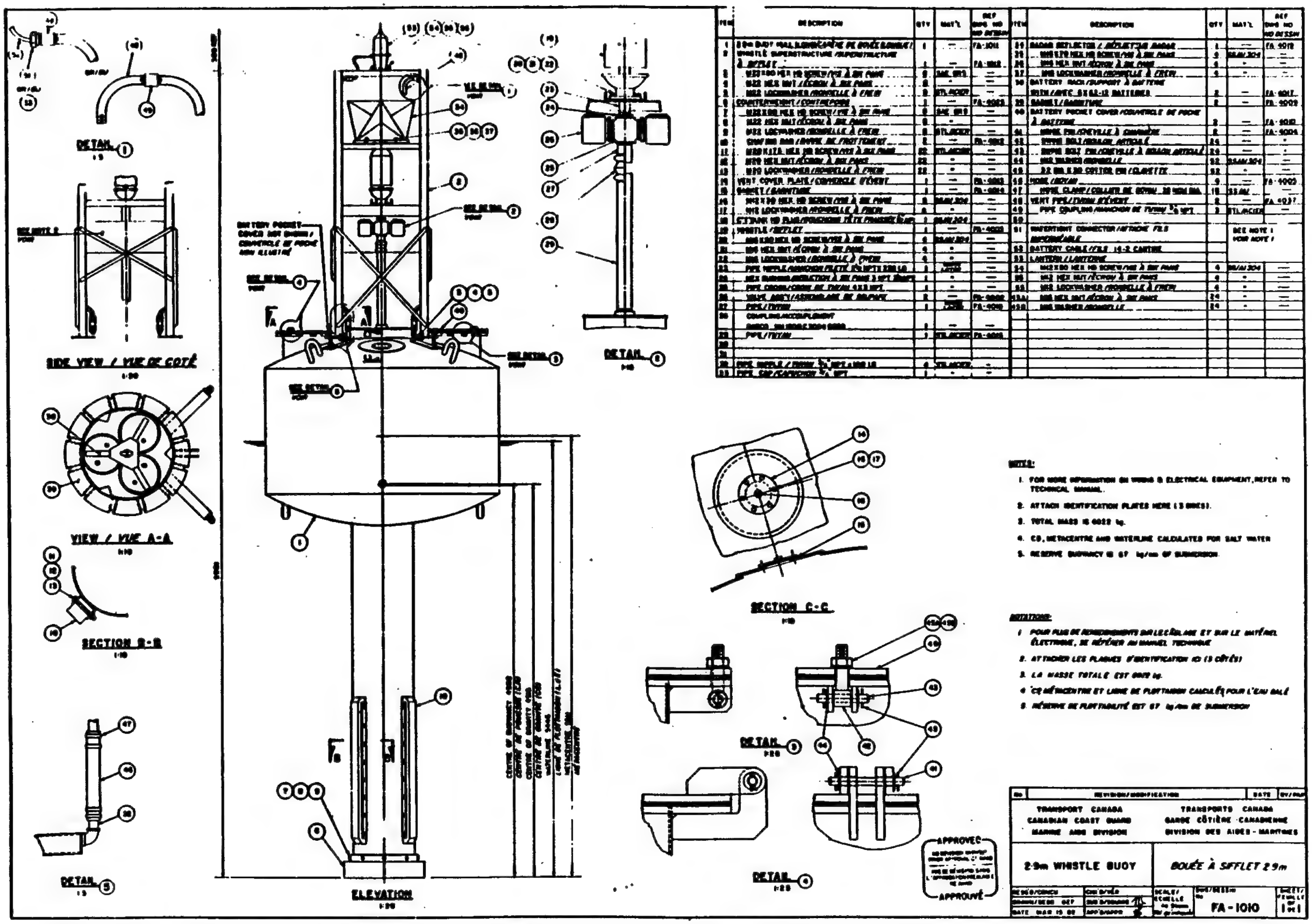

Figure 3.4 Photocopy of a design drawing for a 2.9 metre whistle buoy (Canada Department of Transport, 1982)

A prime consideration for this, and future, projects is the use of a buoy that is already in service along a channel or fairway. If this is possible, then the cost of the platform will be minimized. Further, if the Coast Guard can place, and/or service, the buoy as a part of their normal maintenance process, then another major cost can be minimized.

Consideration has already been given to determining, or computation of, the height of the GPS antenna above the water's surface with respect to roll and pitch of the buoy. However, the draft, or plane of flotation, of the buoy is also subject to change. Three things must ultimately be determined to resolve any changes in the draft. First, the initial height of the antenna above the water's surface must be measured. There are generally design drawings available for the buoys detailing the dimensions, often including the approximate plane of flotation, as in Figure 3.4. These can be used to estimate the height of antenna above the water's surface, and for design of equipment mounting systems. Final measurements must be made, however, with the buoy out of the water, referring the measurements to some easily recoverable reference system. The final draft, or plane of flotation, must be determined by placing the buoy in the water, and making measurements without disturbing or inducing motion on the buoy. Second, nonlinear changes in the draft may be caused by changing water density, and perhaps by strong currents or large seas. The water density will fluctuate with changes in temperature or salinity, and these must be considered in the design of the data collection. The buoyant force can be described as (Streeter and Benjamin, 1975):

$$F_b = \gamma \int_v dv \tag{3.2}$$

where the density, γ, of the water varies with temperature and salinity, and v is the volume of displacement. The density variation of water is a complex function of the water temperature, salinity, and depth. Tables and graphs can be found in texts on physical oceanography that give density approximations for various conditions (Pond and Pickard, 1978). At a constant salinity of 35 ppt (the typical salt content of the oceans), the density will vary from 1027.5 to 1025 kg/m^3 for a corresponding temperature variation of 0°C to 20°C. Figure 3.5 shows the effect of changing density on the buoy draft, where the draft is found by

$$draft = \frac{m / \gamma}{\pi r^2} \tag{3.3}$$

where m is the buoy mass (4739.2 kg), and r is the buoy radius (1.45 m). At a constant temperature of 10°C, the density varies from 1000 kg/m^3 to 1030 kg/m^3 for a salinity variation of 0 ppt to 40 ppt, the typical maximum range for coastal areas. If a constant water temperature is assumed, the buoy selected for this project will exhibit a change in draft of less than 2 cm from fresh (1000 kg/m^3) to common salt (1025 kg/m^3) water.

Strong currents or large seas may partially submerge the buoy if the scope of the anchor chain is drawn to its limit. This factor may define the field season available for observations. For instance, conditions can become severe enough to invert the buoys during winter ice buildup in the northern climates (Hope, 1994).

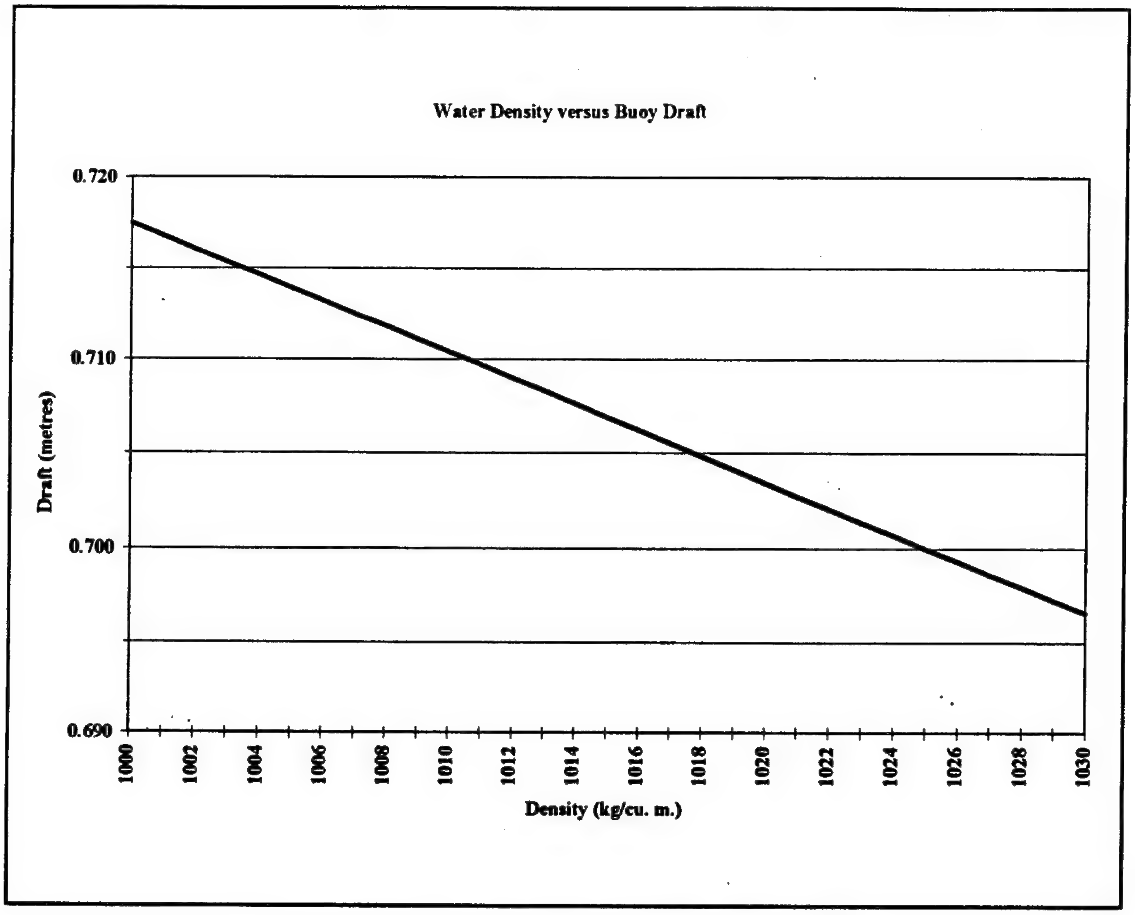

Figure 3.5 Water density versus Buoy draft.

Third, linear changes in draft would be a result of gradual sinking (or rising) due to changes in the buoyancy. Therefore, no material can be added to, or taken from, the buoy once on station. Further, the draft must be checked on some regular basis, and, at a minimum, before and after the collection of each data series.

Modifications to the buoy include mounting an equipment housing at the base of the bell structure, fabricating and installing a 12V and 24V "bus bar" for the electronics, and painting 4 "staffs" along the draft line. Other than the GPS equipment installation, the work on the buoy consisted of painting draft markings, performing a survey of these markings in the shop, and installing the 12 and 24 V dc power systems. The draft

markings were painted using the same triangular pattern as the CHS tide staff. Four scales were painted, each on an opposite side (see Figure 3.6 and Table 3.6). Each point on the scale was 10 cm, and the markings were black on a background of the yellow buoy. Several days were spent performing a survey of the buoy, while it lay on it's side, in the shop to establish the dimensions of the GPS antenna phase center to the 0 mark of each draft scale.

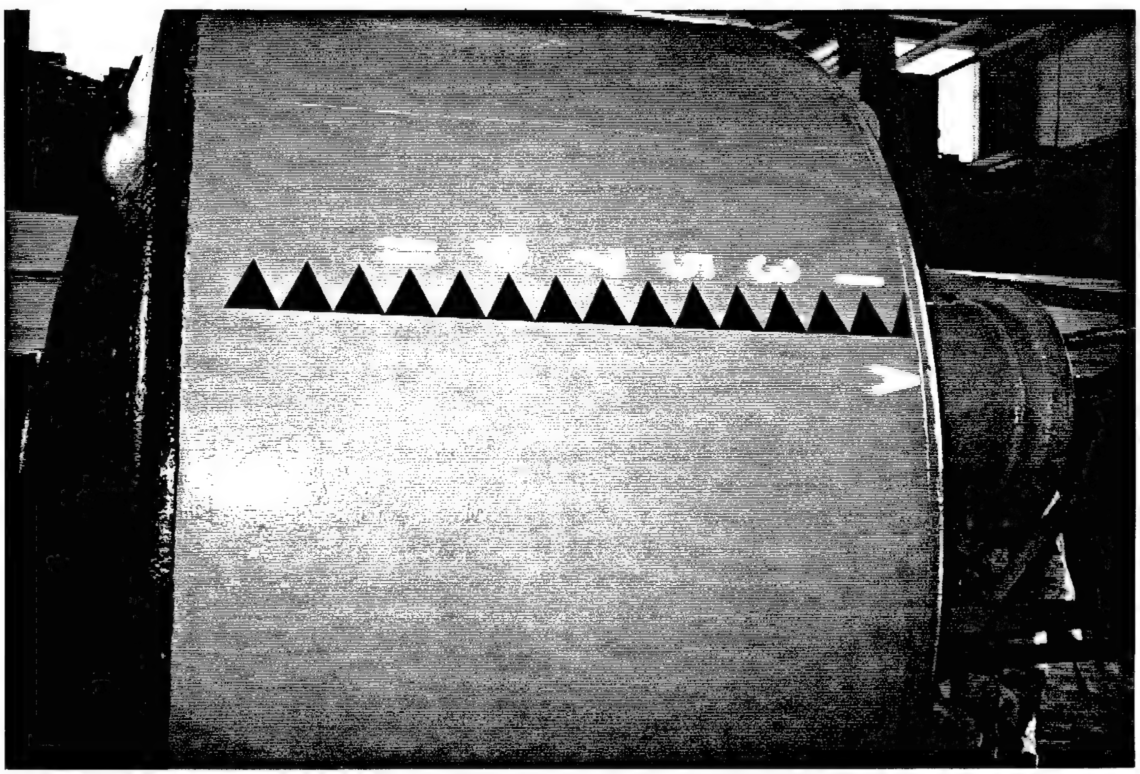

Figure 3.6 The buoy, laying on its side in the shop. The "A" draft scale in decimeters.

The buoy's power system consisted of 24 "long packs," manufactured by Eveready Division of Ralston Purina, Canada. These are essentially a large battery composed of many smaller dry cells and are specially made for installation in the CCG's

buoys. Each long pack is rated at 12 V dc, 350 A. A 12 V system was made to operate the notebook computer, the VHF radio, and the GPS receiver. This system connected 18 of the batteries, for a total of 6300 A at 12 V. A 24 V system was installed to operate the TSS pitch/roll/heave sensor. This system connected six batteries, for a total of 1050 A at 24 V. The power requirements are given in Table 3.7.

Table 3.6 Buoy antenna heights.

Scale	Antenna to zero mark on scale
A	4.058 m
B	4.113 m
C	4.082 m
D	4.061 m

All modifications and handling of the buoy were performed by the CCG. Equipment installation on board the buoy was performed by personnel from the UNB, USACE, and the CCG as appropriate, and as directed by the CCG. The CCG facilities, and Saint John itself, proved to be a very good location for this project. The buoy, carpenter, and machine shops at the CCG base were invaluable to the successful operation of this project. Further, the crew of the buoy tender, *Provo Wallis,* provided very professional and adept buoy handling, thus protecting the equipment and ensuring a successful deployment.

3.9 GPS Reference Station Considerations

The reference station consisted of a GPS receiver and antenna, a radio, PC, optical disk drive, and associated cables and MODEMS. The equipment was set up on the top floor of the CCG's administrative building, within cable length of the rooftop antenna. This also provided access to a continuous power source, and allowed space for

Table 3.7 Power required on the buoy.

System	Voltage	Power (watts)	Amps / hour
TSS 335B	24	20	0.833, 24 V
Radio, Repco SLQ-96	12	6	0.5, 12 V
GPS 4000 SSE	12	10	0.833, 12 V
Computer (3500TC)	12	56	4.667, 12 V
light	12	10 (1 hour/day)	0.035, 12 V
		Total (per hour) 24 V, 0.833 amp	
			12 V, 6.035 amp

buoy capacity: 24 batteries @ 12 V, 350 amphour

12 V system:

18 batteries x 350 amphour = 6300 amphour
6300 amphour / 6.035 amp = 1044 hours = 43 days

24 V system:

(6 batteries x 350 amphour) / 2 = 1050 amphour
1050 amphour / 0.833 amp = 1260 hours = 52 days

an additional PC to be used for data archival and initial processing and report writing. The most critical requirement was placement of the radio link antenna, followed by a suitable location for the GPS receiver antenna. Because the GPS needs an open view of the sky, the low power radio (4 W) used on this project required a line-of-sight to the buoy.

4. DATA COLLECTION AND PROCESSING

During the course of the field campaign, the data collection process involved downloading data in the form of PC files from various sources, including the two GPS receivers mounted on the roof of the CCG's administration building, the GPS receiver and TSS Motion Sensor aboard the buoy, the Saint John Harbour permanent tide gauge, the Socomar tide gauge in the south slip of the CCG base, and the CHS tide staff located in the south slip. Figure 4.1 shows the data flow from each sensor to the PC used for final data processing. Two notebook PC's were used to process, in real-time, the two OTF GPS baselines (the buoy and the static). The TSS pitch and roll data were integrated into the position file computed with the GPS buoy data. Because of the limited memory capacity of the PC's, the data from the notebook PC's had to be downloaded daily. This was performed by connecting a transportable Bernoulli drive data storage device to each PC and downloading the data from the PC onto 150 Mb

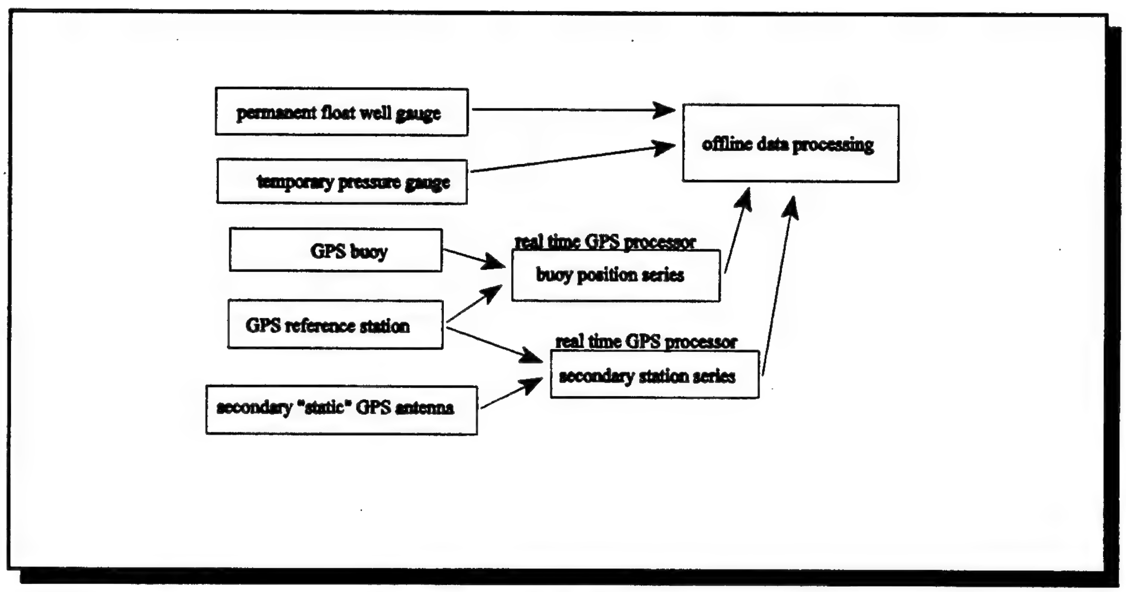

Figure 4.1 Data flow.

disks. The disks were then transported from Saint John to UNB where they were downloaded onto 1 Gb magneto-optical tapes. All final data processing were performed using a PC with a pentium processor and 1 Gb hard drive. A large hard disk, and removable disk capacity, was required to support the volumes of data being recorded on a daily basis. Table 4.1 outlines the types and volumes of data generated per day by the systems used in this project.

Each GPS receiver generates raw measurement files in a binary format. These files were automatically combined in the notebook PC's for real-time processing. For example, the data from the buoy and the reference station were combined for computation of the carrier based position of the buoy. A by-product of the computation was the differential code position of the buoy. The computations occurred once each second, resulting in a 1 Hz time series of code and carrier based positions. (The same situation existed for the static baseline.) The result is a raw binary data file from each GPS receiver, a file of code based positions from each "rover" (buoy and static), and a file of carrier phase based positions from each "rover."

Table 4.1 Daily types and volume of data collected.

Type of Data File	Volume Per Day
Buoy and Static OTF Carrier Positions	17 MB
Buoy and Static Differential Code Positions	15 MB
Buoy, Static and Reference Stations Raw Data	135 MB
Saint John Permanent Float Gauge	5 KB
Socomar Pressure Tide Gauge	15 KB
TOTAL	167 MB

The OTF carrier phase position files contain the buoy and static antenna heights. These are the files that were reduced to a time series for tidal analysis and comparison with the other "conventional" tide gauges and for the computation of mean tide values. The binary files were collected solely as a backup, in the event that post processing of the GPS results was required. Finally, the differential code position files were saved for future examination of the performance of differential code positioning.

4.1 Duration of Data Collection

Figure 4.2 shows the period of time that each gauge logged data during the field campaign. The data series from the Saint John Harbour permanent tide gauge and the Socomar pressure gauge in the south slip of the CCG base were continuous throughout the field campaign from June 1, 1994 to July 24, 1994. A few days after the buoy was set offshore, to the south of Partridge Island, a fuse blew in the GPS receiver and data transmission ceased from the buoy until the fuse was replaced. The buoy, in its offshore position, resumed transmission on June 15, 1994, and operated continuously through June 29, 1994 when its power requirements exceeded the power supplied by the 12 V and 24 V dc systems on board. On July 13, 1994 the CCG vessel, *Provo Wallis*, was able to retrieve the buoy. The buoy was moored on the south side of the CCG base in Saint John and it resumed transmission of data on July 14, 1994 and was terminated on July 24, 1994.

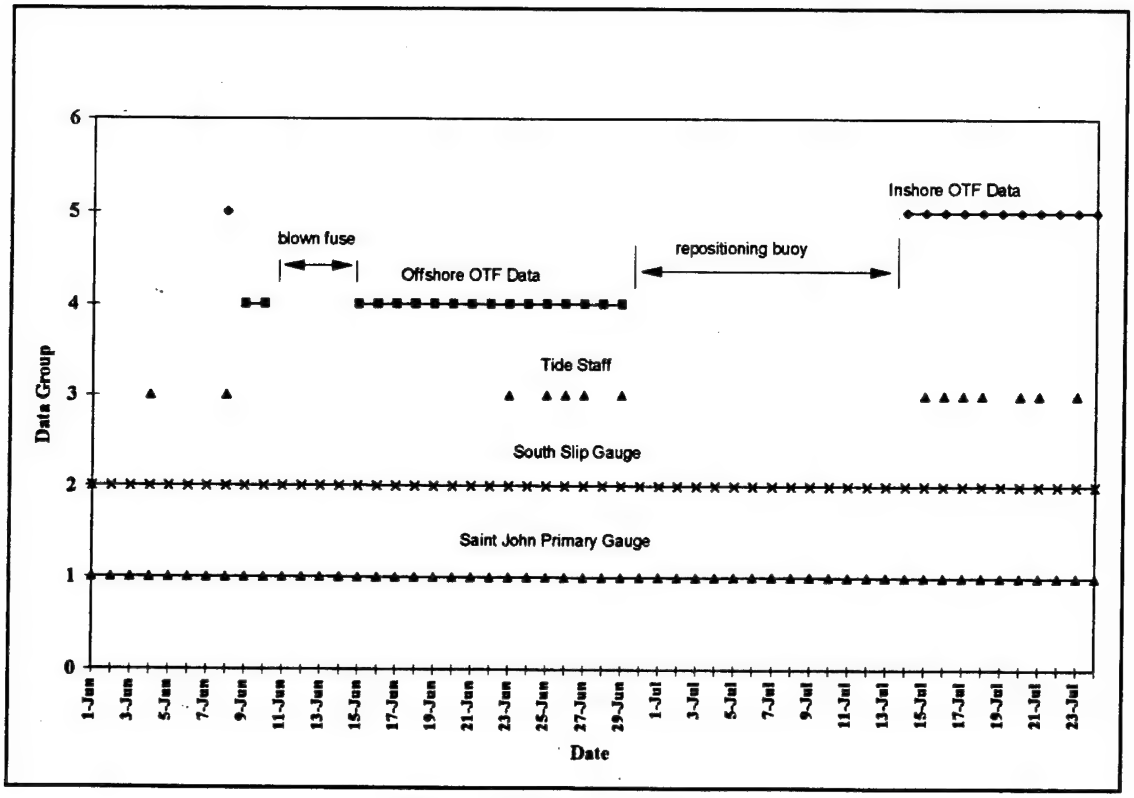

Figure 4.2 Data collected.

4.2 Buoy Draft

The draft of the buoy was measured on four occasions while the buoy was located offshore, south of Partridge Island. The readings were made by averaging visual observations of each scale. The site visits were conducted at the beginning and end of the data transmission, and twice in the interim. The average reading of the four draft scales, added to the height of the antenna above the 0 mark of each scale, results in the height of the antenna above the water surface (after correction for pitch and roll). Figure 4.3 shows a graph of the readings with a mean of 4.787 m. When the buoy was repositioned south of the south slip at the CCG base, another set of readings was taken. Figure 4.4 shows that the mean buoy draft while inshore was 4.795 m.

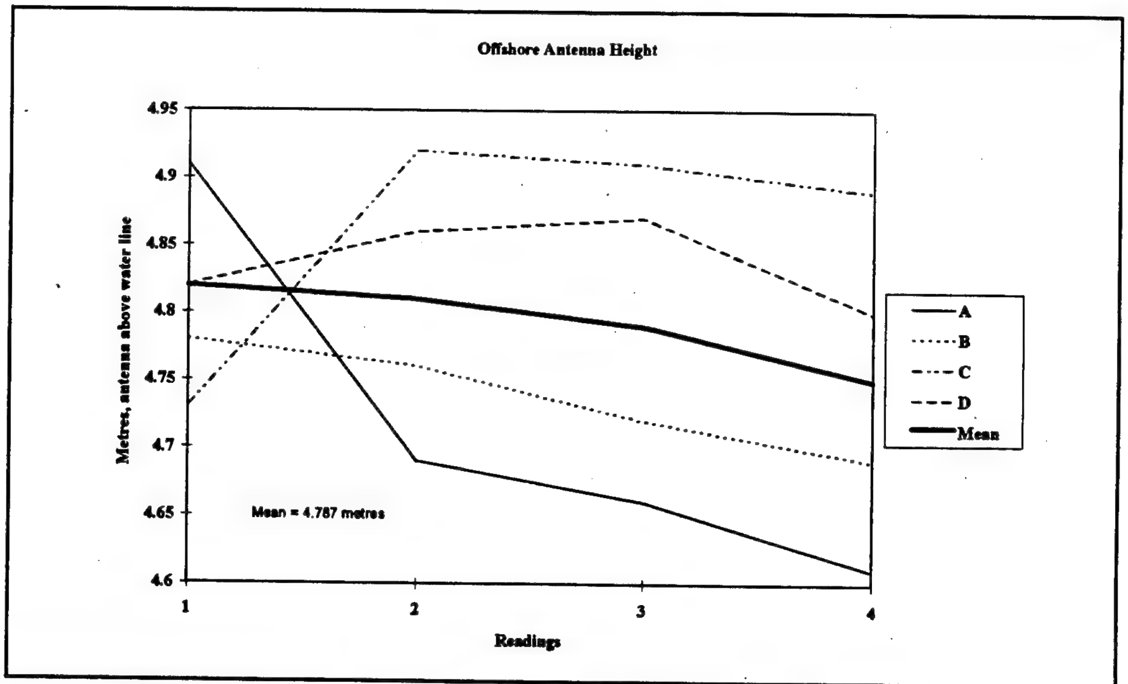

Figure 4.3 Buoy, offshore antenna height (before pitch and roll correction).

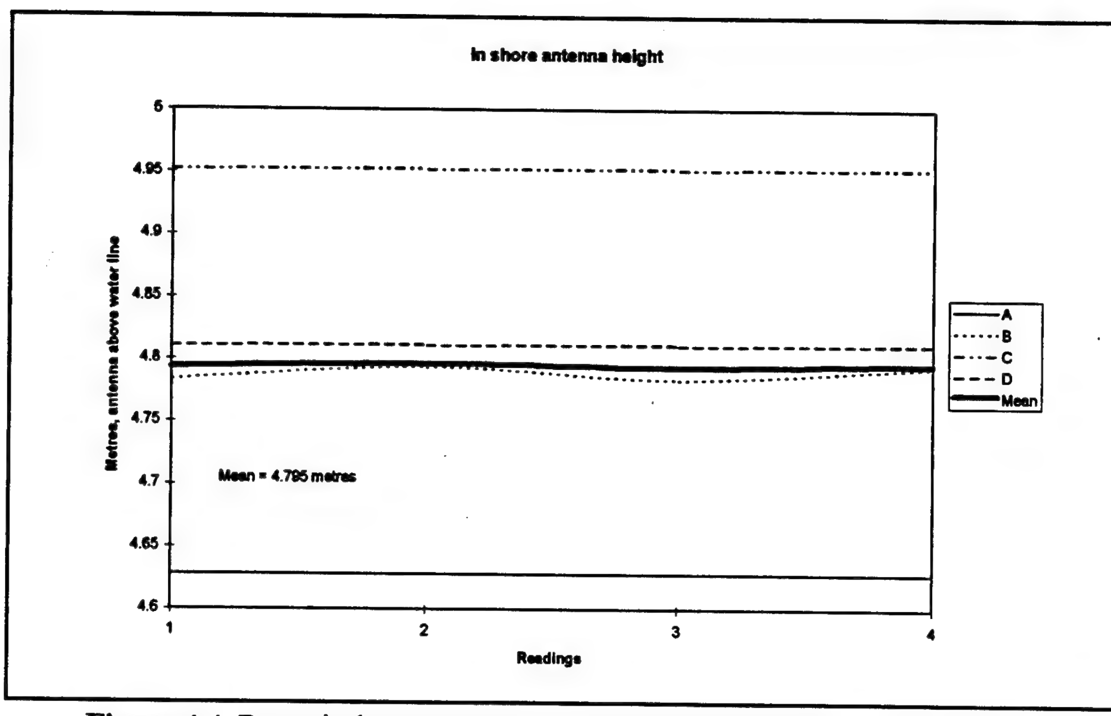

Figure 4.4 Buoy, inshore antenna height (before pitch and roll corrections).

4.3 Processing and Data Reductions

Both the CHS and NOAA use hourly height values for datum computations (Martin, 1994 and O'Reilly, 1994). NOAA also uses the daily high and low waters. Therefore, if existing software and tidal analysis computations are to be used, a method is required to reduce the 1 Hz GPS data to a series of hourly heights and the daily high and low waters. Existing gauging systems rely on some form of mechanical damping of wave action to determine and log heights at intervals of a few minutes (NOAA standard is 6 minutes). NOAA then uses a polynomial curve fit to automatically compute the daily highs and lows.

An unknown component of this project was the optimum method of reduction to transform from the 1 Hz GPS time series to the 1 hour time series for tidal analysis. One thought was to filter the high frequency noise of the wave induced buoy motion and then curve fit the data series to compute the hourly values and the daily highs and lows. An alternative was to average the 1 second sampled series over a 6 minute period to match the data series typically collected by the NOAA (Martin, 1994), or a 15 minute period as used by the CHS. This would enable NOAA, or CHS, to directly use the GPS data in their analysis process. The process selected was the same as used by the Socomar gauge. A mean running average was computed using 40 seconds of data, corresponding to each sample from the two conventional gauges.

One failure of this project was the recording of the raw GPS data. These binary files averaged about 45 Mb each day for each receiver. They were to be used to post process the carrier phase based positions in order to examine anomalous data. During

the data transfer process from the notebook PC's operating the GPS systems, to a larger storage device, most of the binary files were corrupted. Therefore, only the positions computed in real-time by the system were available for further analysis.

The remaining data were processed in the following sequence:

1. Each data series was downloaded to an organized file structure on a PC.

2. The draft readings of the buoy were examined, and a mean draft for the inshore and offshore series was computed.

3. The data series from the buoy was transformed to a water surface elevation, at a 1 second sampling rate.

4. The GPS derived water surface heights were filtered to match the sampling rate of the float gauge and the pressure gauge.

5. The data series from the GPS buoy, a float gauge, and a pressure gauge were merged into a single file for data comparisons.

6. The data from the stationary antenna mounted on the roof were plotted, and a daily mean height and a standard deviation were computed.

7. The stationary data series was filtered to detect outliers.

4.3.1 Rotation of an antenna to water surface height To compute the effects of pitch and roll of the buoy and to remove this effect, the height of the antenna was rotated down to the water surface elevation. This was performed by the following formulation (Massingha, 1994):

$$\psi = \sin^{-1} \frac{\sin(\beta)}{\cos(\alpha)} \tag{4.1}$$

where α is the pitch, β is the roll, and ψ is the effect of roll in the new reference frame, after the pitch is considered. The untilted height of the antenna above the water surface, H^b, is then rotated into the instantaneous, tilted height of the antenna above the water surface, $H^b(t)$, by;

$$H^b(t) = H^b \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\psi) & \sin(\psi) \\ 0 & -\sin(\psi) & \cos(\psi) \end{bmatrix} \begin{bmatrix} \cos(-\alpha) & 0 & -\sin(-\alpha) \\ 0 & 1 & 0 \\ \sin(-\alpha) & 0 & \cos(-\alpha) \end{bmatrix} . \tag{4.2}$$

Then $H^b(t)$ is substituted into equation (2.12) or (2.13) as appropriate.

4.3.2 Buoy series filter The buoy data were collected at a 1 second sampling rate, while the two "conventional" gauges logged data at either a 6 or 15 minute rate. Therefore, the buoy data were filtered to create a matching series. The filter also served as a means to dampen the heave induced motion created by wave and current effects on the buoy. This motion was observed several times when the buoy was offshore. The buoy would "bob," the draft changing rapidly, with respect to the actual rise or fall of the tide. The final time series of the buoy was computed by the running mean filter

$$H_{\Delta}^{w} = \frac{\sum_{i=-19}^{i=20} H^{w}(t)}{40} \quad , \tag{4.3}$$

where H_{Δ}^{W} was set to match the time series of the Saint John permanent gauge and the Socomar pressure gauge.

5. ANALYSIS AND RESULTS

This chapter discusses the overall performance of the "GPS buoy" as related to two independent "conventional" gauges operating in the vicinity of the buoy, and the ability of the GPS technique to successfully meet the three primary project objectives. The first objective was to demonstrate the ability to establish a datum at a location that hinders the use of conventional gauging techniques. The second was to provide a data series sufficient for the CHS and NOAA methods of datum determination. The third was to recover a datum.

In addition to the collection of tidal data, a GPS data set was collected and processed identical to the buoy, but occupied by a static baseline. This stationary data set yields what is the present accuracy of the OTF GPS technique, over a short baseline.

No independent studies of the accuracy or precision of the two "conventional" gauges (the Saint John permanent float well gauge or the Socomar TMS 1000 pressure gauge) were conducted. The basic assumption was that these two systems represented the industry standards, and the GPS should be tested against them. By using three independent systems, they can be compared against each other to assess the suitability of the GPS and to evaluate any problems in the data.

5.1 Data Reduction Process

As discussed in Chapter 4, there were four primary data sets produced from this project: the heights of the "static" antenna; the water surface heights from the GPS buoy; the water surface heights from the Saint John permanent gauge; and the water

surface heights from the Socomar pressure gauge. These data sets were time matched, and entered into a commercial spreadsheet software package (Microsoft Excel) for direct comparisons and calculation of mean values. The goals of the first objective were evaluated by reviewing the operation of the system during the offshore mooring. Because there were no independent gauges collocated with the buoy during the offshore data collection, there were no independent checks on the accuracy of the data. The second objective, data collection suitable for the CHS and NOAA methods of tidal datum computation, was evaluated from 1) the duration of the data series, and 2) digital filtering of the 1 second series to match the series produced by the CHS permanent gauge in Saint John. The final objective, datum recovery, was demonstrated during the inshore mooring.

Each system (the GPS and the two conventional gauges) operated with its own clock. The GPS output solutions in GPS time was 9 seconds ahead of UTC. The Saint John permanent gauge operates in Atlantic Standard Time (AST), and was converted to UTC during data processing. The Socomar pressure gauge was set to operate in UTC. The clocks on both of these gauges were manually set by CHS personnel using a wrist watch that had been recently coordinated with a Canadian time standard signal.

5.2 General OTF Buoy Operation

The first objective was to demonstrate the ability to establish a datum at a location that impedes the use of conventional gauging techniques. From the U.S. perspective, only a few days of data are required when using the method of simultaneous

observations, although the preferred series would span 30 days (Martin, 1994). In Canada, the preference is for 2 months of data to perform a harmonic analysis, with 30 days acceptable. As in the U.S., if simultaneous observations are used, then only a few days of observations are required (O'Reilly, 1994). Based on these considerations, the intent was to collect 30 days of continuous data at a 1 second sampling rate from the buoy, while operating at an offshore mooring.

After installing the equipment suite in the buoy housing, several days were taken to operate the system and trouble shoot the real-time data transmission and OTF computation. Data transmission from the buoy, with a VHF radio, was used to eliminate data storage on the buoy, and to allow real-time data processing. This processing provided a measure of quality control to the project, ensuring proper results as they were collected. A limiting factor of this radio was that it required line of sight for transmission to the reference station, and it proved to be a significant drain on the buoy's power system. The transmitting radio and a small amount of transmission antenna cable were inside the equipment housing, close to the GPS receiver and the GPS receiving antenna cable. This created interference and required insulation of the VHF radio and transmitting antenna cable with a nonferrous material.

5.2.1 Power The battery power on the buoy had been selected to yield 30 days of continuous operation of all the equipment. There was almost no knowledge of the specific operating characteristics of each piece of equipment prior to the data collection. The operating voltages for each unit on the buoy are listed in Table 5.1. To support

both 12 and 24 V requirements, the batteries were divided into two separate power systems. Only the TSS unit was placed on the 24 V supply. Unfortunately, the GPS receiver did not continue to operate below about 11 V. As shown in Figure 5.1, the power system dropped from above 12 V to 11 V by June 15, 1994. It appears that after a rapid draw down, the operating voltage of the total system was about 10.8 V. As a result, the GPS receiver would not function on the 12 V supply after June 15, 1994. At that time, the buoy was visited, and the GPS receiver was transferred to the 24 V supply along with the TSS sensor. This switch reduced the total data collection to about 14 days because of the smaller total wattage of the 24 V supply.

Table 5.1 Operating power requirements.

System	Operating Voltage Range
TSS 335B	20 - 30
GPS 4000SSE	10.5 - 35
Radio, Repco SLQ-96	12.5 (± 20%)
Computer	12

5.2.2 OTF positions In general, the buoy positions were computed automatically, in real-time with a reasonable degree of robustness, yielding a continuous record at a 1 Hz sampling interval. However, the system would skip individual epochs, losing a single update every few minutes, leaving a gap in the 1 Hz record. This problem appeared to be a function of the capacity of the transmitting radio and would probably be eliminated if the data span was set at 2 seconds, or the radio broadcast rate increased to 9600 baud (Barker, 1994). This situation would also be eliminated if the data were

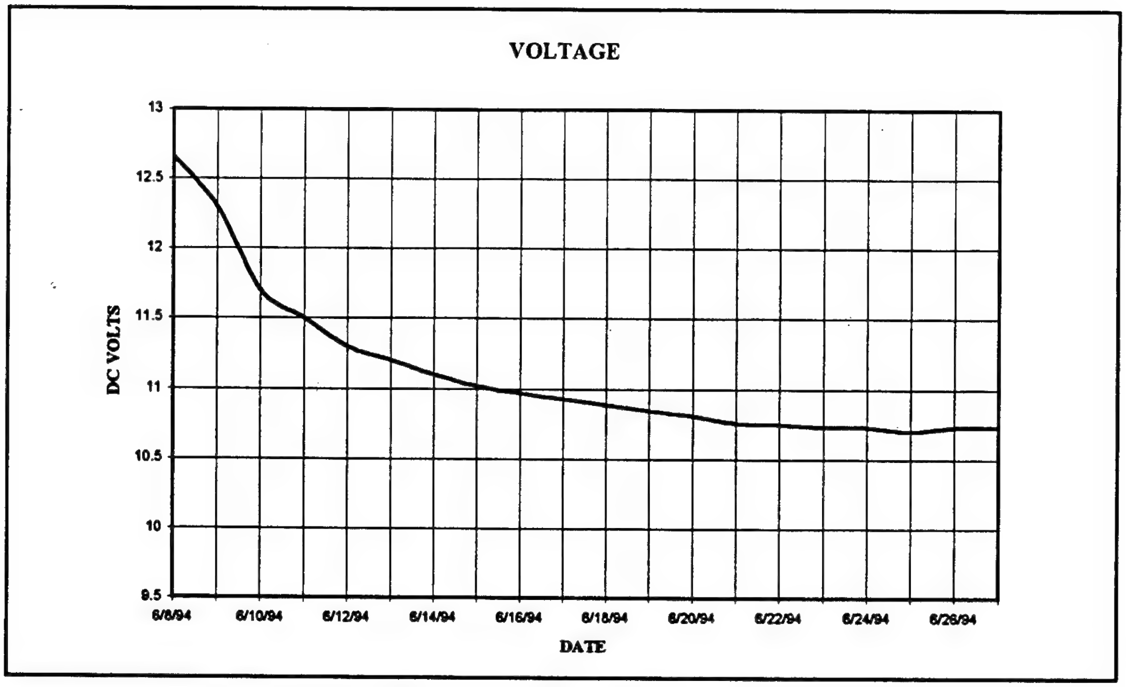

Figure 5.1 Buoy voltage.

collected at each GPS receiver and post-processed.

Occasionally, the OTF system would also select, and initialize, on the wrong set of integer ambiguities. These data were easily detected and filtered out of the series, but did require a significant amount of data checking. Figure 5.2 shows about 1 hour of buoy heights at a 1 second sampling interval. The wave induced motion was about one half meter, and the tide rose from about 5.5 to 7.0 m during the hour. The data collected with bad integer resolution were obvious. When a tidal series contains erroneous data, it is standard practice to reject those data points, and to infer or interpolate values from data points before and after the gap by comparing their relationship to the "control" station. In this case, the Saint John permanent gauge was used as the control station, and a 15 minute sampling interval was used for comparison and inference.

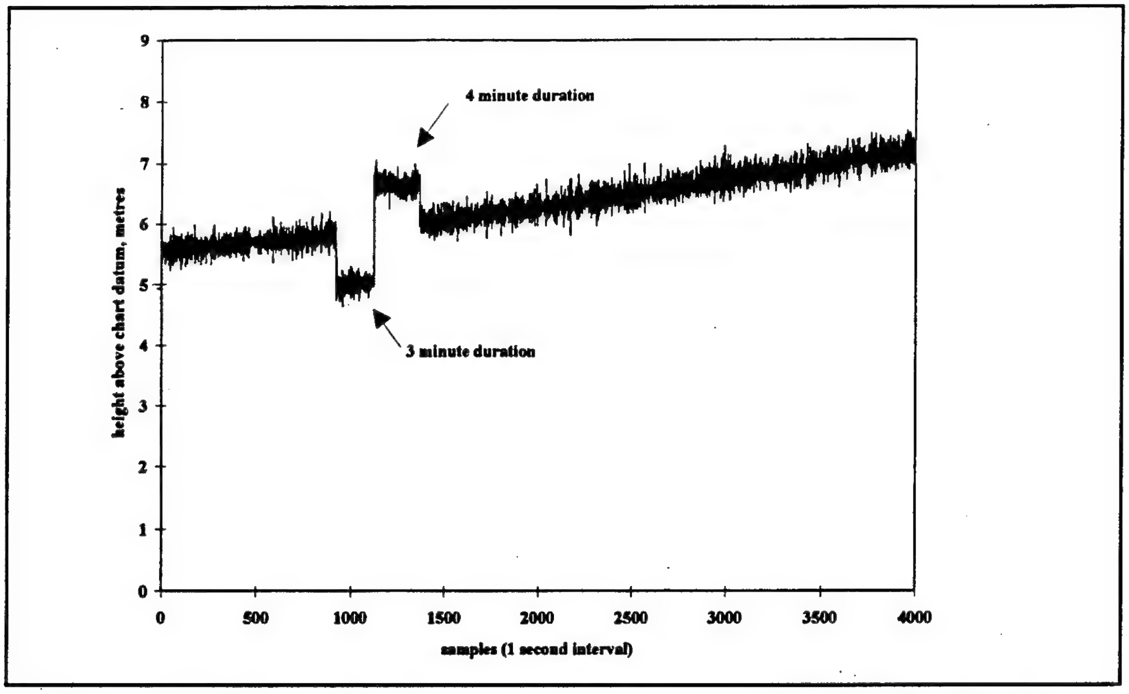

Figure 5.2 GPS based buoy heights, with resolution of wrong integer ambiguities.

5.2.3 Buoy draft The buoy draft measurement proved to be cumbersome, although extremely simple in concept. From the results of the inshore data collection, it appears the accuracy of simply reading the scales was adequate. However, during the offshore mooring, the readings were taken infrequently, only when a boat was available. The wave induced motion was quite severe, making the readings more difficult. An attempt was made to take several readings and use the resultant mean, although it is not clear how accurate this process was. Further, the draft scales became fouled by the end of the offshore mooring (33 days) and required cleaning for the inshore mooring.

5.3 Static GPS Baseline

The accuracy of height determination of the water's surface from buoy

measurements included errors from the OTF GPS, the height transfer from local tidal benchmarks, the reduction of roll and pitch, and the buoy draft readings. Therefore, the second, stationary, GPS antenna mounted on the roof of the CCG's administration building was used to evaluate the accuracy and precision of the OTF GPS system.

A total of 20 days of 1 second data was collected from the static baseline. Because of computer hardware constraints, the data sets were broken into daily files of about 24 hours each. The days were not contiguous, because the receiver on the static baseline was periodically used for other projects occurring in the area. In total, about 1.5 million data samples were taken. An individual sample is simply the height, $H(t)$, provided in real-time by the OTF system. This height was computed by the system using (from equation (2.13))

$$H(t) = d + H^{a} + \Delta h(t) - H^{b} \tag{5.1}$$

where; d is the height of the reference station found by running spirit levels from tidal benchmarks in the local area, H_a is the height of the reference antenna phase center above the station, $\Delta h(t)$ is the ellipsoidal height difference as determined by the OTF GPS, and H_b is the height of the roving (static) antenna above its station.

Two days of data are plotted in Figures 5.3 and 5.4 depicting "typical" data, each about 24 hours duration with a 1 second sampling interval. The first, July 19 1994, is from a day during which the integer cycle ambiguities were always resolved correctly. The second, July 21 1994, contains short spans where the integers were resolved incorrectly.

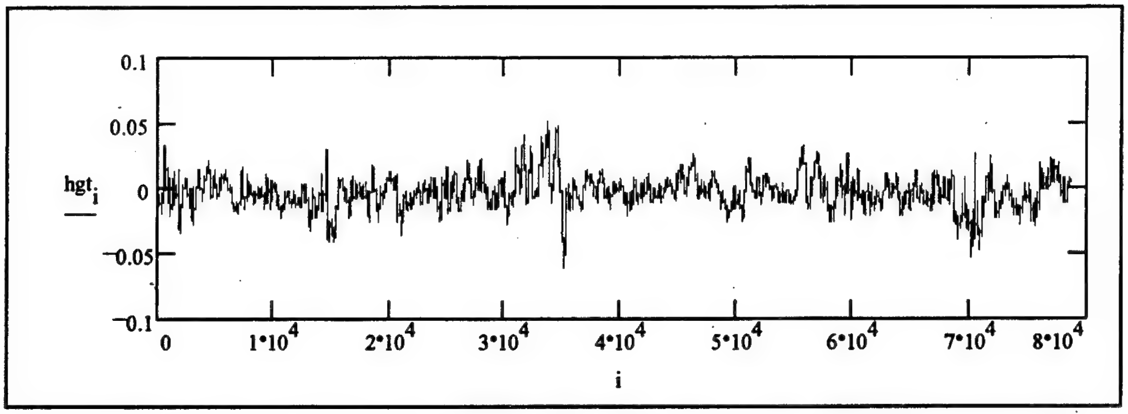

Figure 5.3 July 19, 1994, 24 hours of static heights from the OTF system, all ambiguities resolved correctly. The vertical scale is from -0.1m to +0.1m.

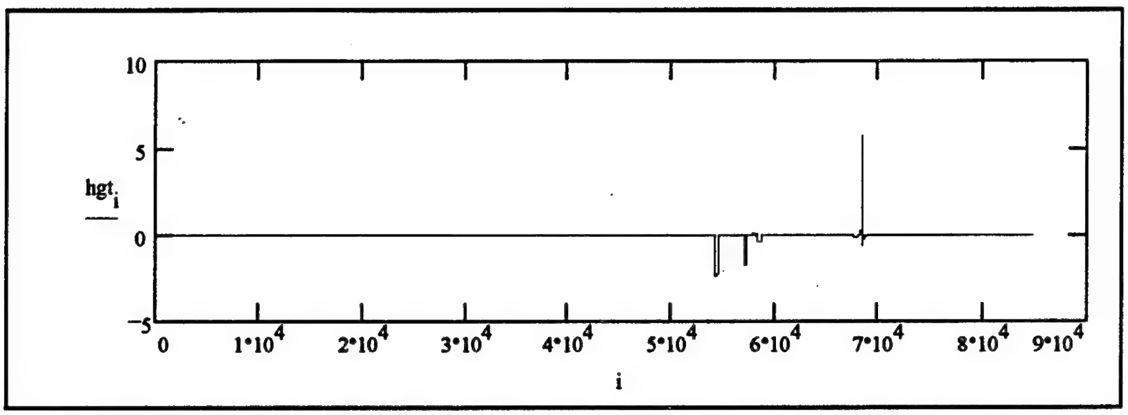

Figure 5.4 July 21, 1994, 24 hours of static heights from the OTF system, some ambiguities resolved incorrectly. The vertical scale is from -5.0m to +10.0m.

Next, the entire time series, broken into daily blocks as in Figures 5.3 and 5.4, were run through a filter, subtracting the known antenna height from the OTF GPS determined height, and rejecting all data above or below a preset threshold, beginning at 1 cm and increasing to 10 cm. The percent of data accepted at each level is shown in Figure 5.5. Approximately 97 percent of the heights are within 3 cm of the "truth," and above 4 cm there is almost no increase in the quantity of data rejected. It appears that about 1 percent of the data is derived from the resolution of incorrect integers. In the

context of a time series with a 1 second sampling interval, this would equate to about 14.4 minutes of "bad" data in a 24 hour day.

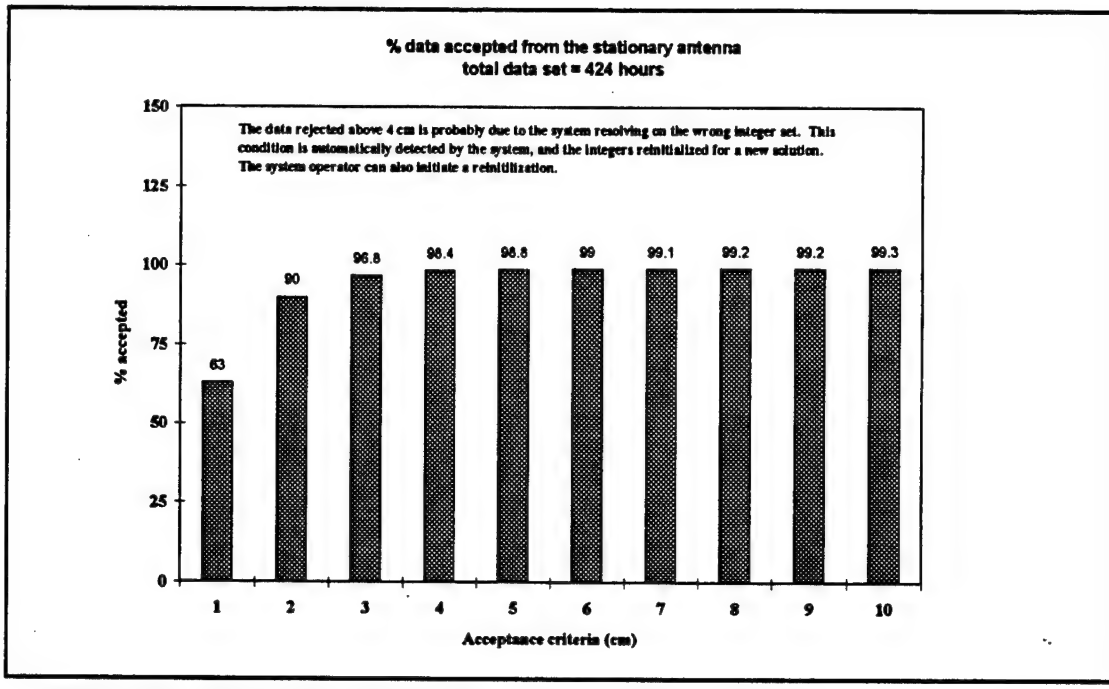

Figure 5.5 OTF-computed heights, percent of data within limits, from 1 to 10 cm.

Considering any data point more than 3 cm from the truth as an outlier (a 3 cm rejection criteria), the mean height and standard deviation of each daily data set was computed (see Figure C1, Appendix C, for a plot.) The mean height is consistently 3 mm below the "truth." This 3 mm is a function of the errors in the height transfer by spirit level from one end of the baseline to the other, and the error in the exact vertical location of the two GPS antennae electronic phase centers. Because of the short baseline (1 m), most of the error is probably in the variation of the antenna phase centers.

5.4 Effects of Pitch and Roll

The height of the GPS antenna on the buoy, above the water's surface, was a function of the vertical distance from the phase center to the draft line, the heave, or dip, induced by wave and current forces acting on the buoy's hull, and the angular pitch and roll of the buoy. The heave effect was minimized by implementing the mean running filter shown in equation (4.3). The pitch and roll were naturally induced by wave and current action, but equally important was the fact that the buoy trimmed out with a tilt of several degrees in calm water. Therefore pitch and roll measurements were necessary for this project even without a wave induced motion. The TSS pitch and roll sensor was initialized to use the normal to gravity as 0° pitch and roll. The OTF data string from the buoy also contained the pitch and roll at a 1 second sampling interval. The angular values were used to transform the height of the antenna to a water surface height with equations (4.1) and (4.2). The effect on the difference in height between the antenna and water's surface due to pitch and roll (combined and referred to as tilt) was maintained in separate files, one for each day. From these files, the daily mean and standard deviation of the tilt effect was computed. From Julian day 161 to 177 (June 10 to June 26, 1994), the buoy was offshore, and the standard deviation of the tilt was more irregular. On Julian day 196 (July 15, 1994), the buoy was at the inshore mooring, and the standard deviation of the tilt was consistently less than 1 cm. During the entire data collection, the mean tilt effect on the antenna height was about -2.5 cm (see Figure C2). The maximum tilt experienced was about 25 degrees from vertical, with a height effect of over 40 cm.

5.5 Offshore Mooring

The principal objective of the offshore mooring was to evaluate the ability to establish a tidal datum at a location that hindered the use of more conventional techniques, such as an offshore location with no fixed structure to attach a float well or pressure sensor. The location chosen was in the open waters of the Bay of Fundy, just to the south of Partridge Island, on the outside of the breakwater protecting Saint John Harbour. On June 9 1994, the day of installation, the electronics on the buoy were turned on while the buoy rested on its side on the deck of the buoy tender, *Provo Wallis*. When the vessel had maneuvered to the selected location, the buoy was lifted off the deck and set overboard, using standard CCG procedure. The OTF GPS system was actually broadcasting data with the buoy still on the deck. Placing it in the water made no impact on the system itself. The electronics operated for a total of 21 days, with 5 days data lost because of a blown fuse on the GPS receiver, and 4 days lost because the 24 V supply dropped too low for operation of the TSS. Therefore, the system as designed was not capable of providing 30 days of data for the standard datum reduction techniques of the CHS or NOAA. There are, however, 10 continuous days of "good" data that is satisfactory to conduct a water level transfer with simultaneous observations. Figure 5.6 shows 2 days of GPS buoy data collected offshore plotted against the corresponding 2 days of data from the Saint John permanent gauge. All data gaps, and blunders (OTF resolution on bad integers) have been resolved, and the GPS data filtered to time match the 15 minute sampling interval of the data series from the permanent gauge. An analysis of the data collected is given in Section 5.7.

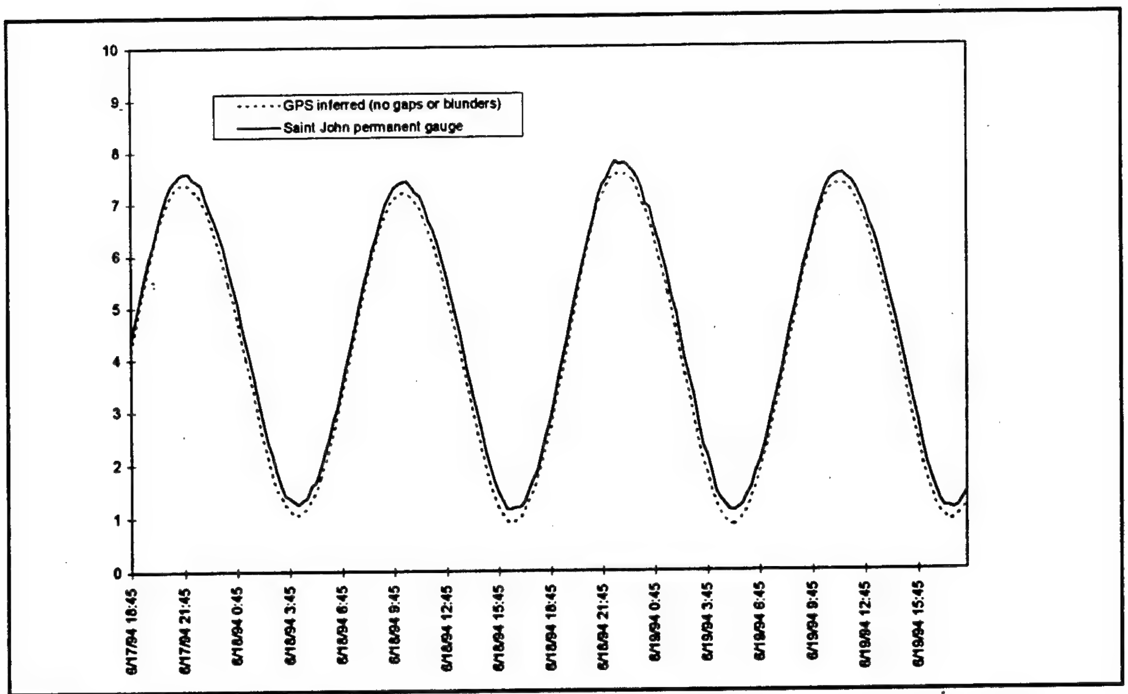

Figure 5.6 Two days of tide heights, from the GPS buoy and the Saint John permanent gauge, during the offshore mooring. The bias between the two is a function of the change in height of the water surface with respect to the ellipsoid.

5.6 Inshore Mooring

The inshore data set is intended to examine the accuracy with which GPS follows the tide, thereby demonstrating a datum recovery and creating a data set that could be used to compute simultaneous observations. This data set was collected in the Saint John River within a few hundred meters of both the Saint John permanent gauge and the Socomar pressure gauge. The buoy was powered from shore, therefore no problems were encountered owing to limited power supplies. The only difficulty arose in securing the buoy to the wharf, such that it did not contact the wharf face and damage the buoy or wharf, or block the line of sight to the satellites from the antenna. Figure 5.7 is a

photograph of the buoy at about half tide at the inshore mooring.

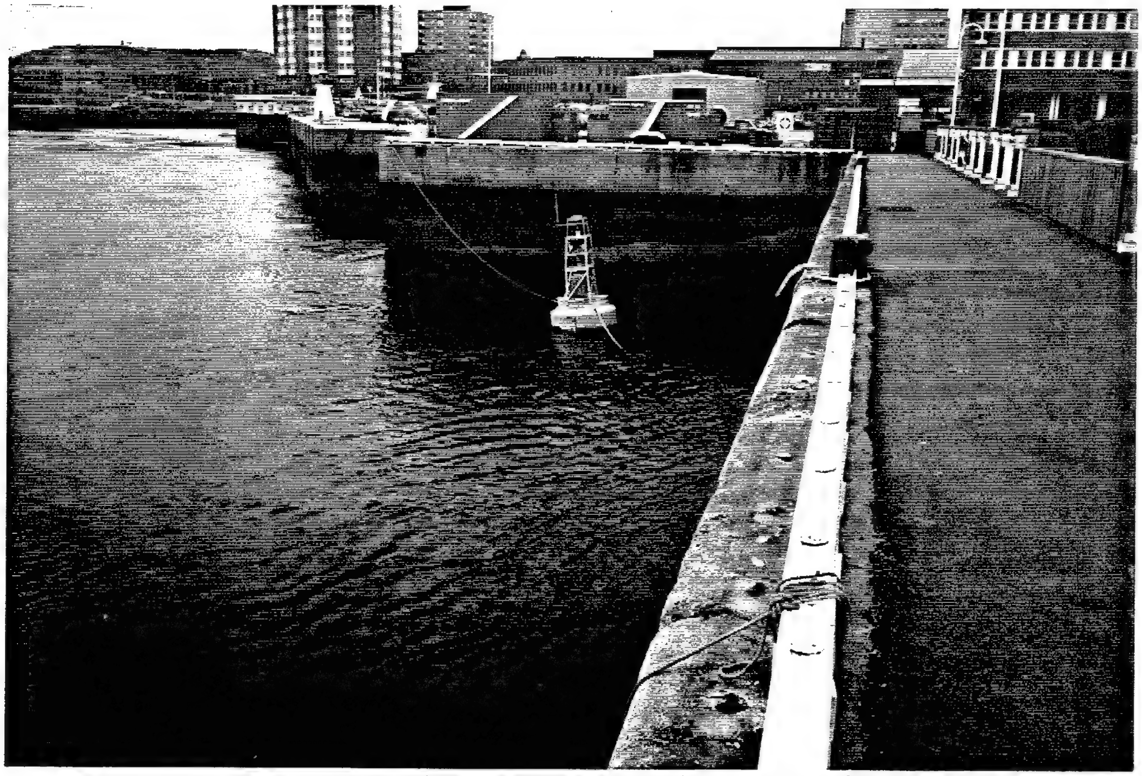

Figure 5.7 The GPS buoy on the inshore mooring.

5.7 Gauge Comparisons

The MTL was computed from the data series collected by the GPS buoy, the Saint John permanent gauge, and the Socomar pressure gauge. The series included the 10 days of continuous data observed by the buoy at both the offshore and inshore moorings. These MTLs, and the 19 year mean tide computed for the Saint John permanent gauge, are plotted in Figure 5.8. The difference between the two "conventional" gauges is 10 mm for both sessions, but in opposite sign. The deviation of the 10 day mean levels from the 19 year mean level is a function of the relationship of the sun and moon to the rotating earth during that 10 day period as compared to the 19 year

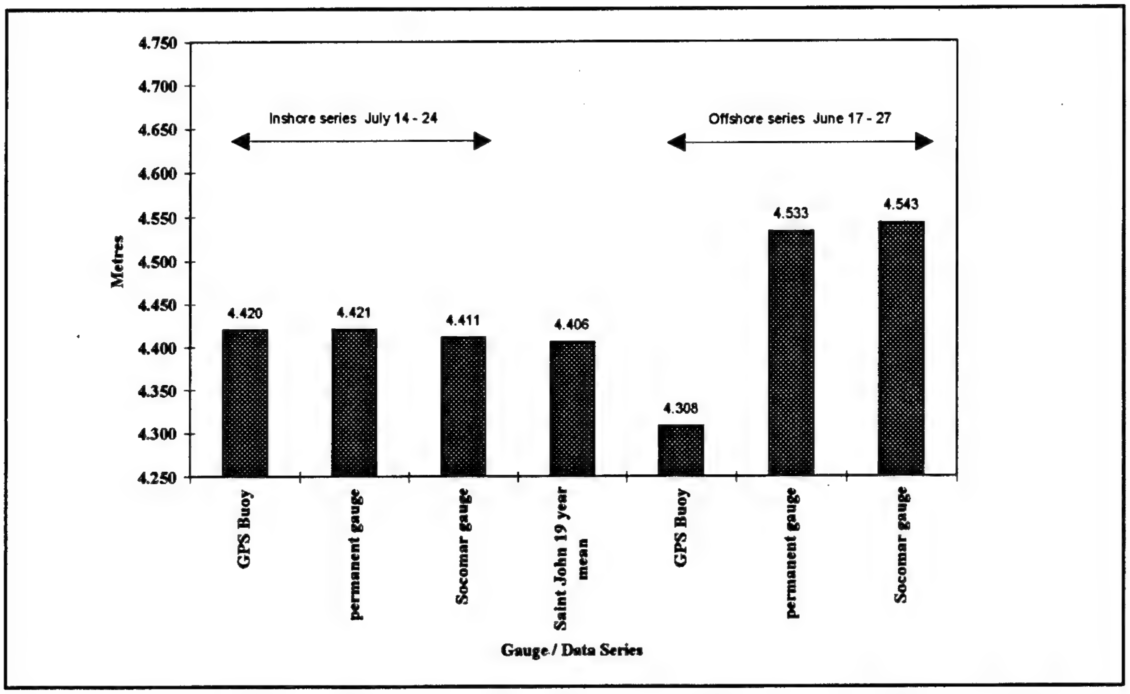

Figure 5.8 Mean tide heights from the project, including the offshore and inshore buoy moorings.

mean of their astronomical relationships. At the inshore mooring, the mean of the GPS buoy is within 1 mm of the permanent gauge and 9 mm of the Socomar gauge. At the offshore mooring, the difference between the GPS buoy and the other two gauges is a function of the change in height of the water surface with respect to the ellipsoid (also Figure 5.6).

To compare the gauges to each other, each series of water surface heights was subtracted from each of the other two, and the differences referred to as residuals, *r(t)*. For example,

$$\boldsymbol{r(t) = h(t)(Saint\ John\ permanent\ gauge) - h(t)(GPS\ Buoy)} \quad . \qquad \textbf{(5.2)}$$

The standard deviation of the residuals was also computed as:

$$SD = \sqrt{\frac{\sum_{t=1}^{n} (r(t) - \bar{r})^2}{n - 1}} \quad . \tag{5.3}$$

Table 5.2 lists the standard deviation of the residuals for each set of differences. It appears that the permanent gauge does not compare as well as the other two (GPS buoy or the Socomar). Plotting the time series of residuals against the actual tide reveals that the maximum residuals occur during mid-tide, or when the tide is rising (or falling) the fastest (see Figure C3 to Figure C8). The minimum residuals are near the times of high and low waters. Although the trend is the same for all the residuals from each set of comparisons, the magnitude of the residuals is lower between the GPS buoy and Socomar gauges.

Table 5.2 Standard deviation of the residuals between gauges.

Series	buoy location	St.dev. (cm)
permanent gauge - GPS Buoy	inshore	7.1
permanent gauge - Socomar gauge	inshore	5.8
Socomar gauge - GPS Buoy	inshore	3.4
permanent gauge - GPS Buoy	offshore	8.6
permanent gauge - Socomar gauge	offshore	5.4
Socomar gauge - GPS Buoy	offshore	5.3

To help explain the trend in the time series of the residuals, each series was transformed to its frequency spectrum with the Fourier Transform, written as:

$$H(f)_n = \Delta \sum_{k=0}^{N-1} h(t)_k \, e^{\frac{2\pi ink}{N}} \tag{5.4}$$

where Δ is the sampling interval, and $f_n = n / N\Delta$. The 6 spectra are shown on Figure C9 to Figure C14. For the two sets of residuals including the Saint John permanent gauge (float - pressure, and float - GPS), the spectra shows definite tidal frequencies, especially the Lunar Semidiurnal terms, with a period of 12.5 hours, and some shallow water constituents, with periods of 3 to 6 hours. In the series of the Socomar vs. the GPS buoy (pressure - GPS) the spectra appears to contain mostly noise with some tidal frequencies beginning to appear.

The permanent gauge is a mechanical float well type, with a float suspended by a spring loaded wire. The water's surface is stilled by a 1 m diameter float well with a 0.1 m orifice, allowing water to flow into (or out of, during a falling tide) the well from the outside river. Because the residuals between the permanent gauge and the other two are a maximum when the tide is rising (or falling) the fastest, a reasonable deduction would be that the river water surface is rising (or falling) faster than the water surface inside the stilling well.

5.7.1 Mean range Establishing a datum at a station of interest generally takes into account the mean range of tide, Mn, whether using harmonic analysis or simultaneous observations. Careful examination of each series revealed that the height of the high and low waters did not match exactly. The ranges for each gauge series during the inshore

observations were computed and are plotted in Figure C15. Ironically, the average range of the permanent station is half way between the average range of the GPS buoy and the Socomar gauge.

The pressure gauge did not compensate (or correct) for any variation in the density of the water column above the sensor. Therefore, if the salinity of the surface water was different than the water at the sensor, then a density gradient would exist that was not considered in the computation of the height of the water column above the sensor. At a constant temperature of 10°C, a salinity gradient from nearly fresh (1005 kg/m^3) to typical salt (1025 kg/m^3) would amount to about 2 cm of error in the height of the water column above the sensor. The buoy draft would also have an error of about the same magnitude, but in opposite sign. Considering that this site is at the mouth of the Saint John River, it is reasonable to expect significant changes in the density of water as the tide moves in and out of the harbor.

5.7.2 Diurnal inequalities The diurnal high water inequality, DHQ, is defined as the difference between two high waters in a day; likewise, the diurnal low water inequality, DLQ, is the difference between two low waters in a day. These values help to describe the type of tide. The DHQ and DLQ for each of the 10 days of inshore data collection are plotted in Figure C16 and C17, and the mean values are in Table 5.3.

Table 5.3 The average range, Mn, and diurnal inequalities, DHQ and DLQ (in meters).

Station	Mn	DHQ	DLQ
permanent	6.83	0.30	0.26
Socomar	6.86	0.31	0.24
GPS Buoy	6.80	0.33	0.24

6. CONCLUSIONS AND RECOMMENDATIONS

A GPS receiver, and supporting electronics, was successfully operated on board a Canadian Coast Guard navigation buoy. It appears that collecting a time series of water surface heights from a GPS instrumented buoy is a viable method for tidal datum determination.

During this project, 10 days of continuous data, at a 1 second sampling interval, were collected at a station in the open waters of the Bay of Fundy. The offshore data collection was terminated when the onboard power supply was exhausted. Ten days of continuous GPS buoy data were also collected from an inshore mooring to allow the GPS results to be directly compared with two other gauge systems located near the buoy. In all cases, the buoy data were transmitted in real-time to the reference station on shore, about 10 km away from the offshore site and within 1 km of the inshore site. The GPS system operated automatically, generating antenna heights in real-time. Subsequent processing reduced the 1 Hz antenna height series to a 15 minute water surface height series for comparison to the two "conventional" gauges. These were the Saint John permanent gauge and a temporary Socomar pressure gauge.

In addition to the water surface measurements, about 20 days of GPS data were collected from a static baseline. These data were used to characterize the performance of the OTF GPS system, without the influence of a moving platform. For this static baseline, only the height values were analyzed. The height component is generally recognized to be the weakest component of a GPS baseline. From the 20 days of 1 Hz data, about 1 percent was more than 10 cm from the truth, while 97 percent was within 3

cm of truth. The mean height from each of the 20 days was about 3 mm below the truth, with a 10 mm standard deviation.

During the inshore data collection, when direct comparisons were made to evaluate system accuracy, the mean water surface heights from the three systems were within a 10 mm spread, with the GPS buoy 1 mm from the Saint John permanent gauge. The daily ranges and diurnal inequalities were within a 6 cm and 3 cm spread, respectively. On an epoch by epoch basis, all gauges were generally within ± 10 cm, with the GPS buoy comparing the best with the Socomar gauge. The permanent gauge appeared to have a lag in the float well that may have caused some of the differences.

6.1 First Project Objective

The first project objective, to demonstrate the ability to establish a datum in a location that hinders the use of conventional gauges, was successfully demonstrated during the data collection just off of Partridge Island. The system was designed to operate for 30 days in support of a harmonic analysis. However, the power drain on the batteries occurred faster than anticipated, and the GPS receiver did not operate at a voltage as low as stated by the manufacturer. Additionally, a blown fuse on the GPS receiver cost several days of data and continued to drain the batteries from the other electronic components. Therefore only 10 days of data were collected, less than the 30 day objective but sufficient for a water level transfer from simultaneous observations with a reference station.

6.2 Second Project Objective

The second objective, creation of a data series sufficient for the CHS and NOAA methods of datum determination, was also partially successful. The GPS buoy data was easily filtered to create a series to match that collected at the permanent and Socomar gauges. The data were not put into an ASCII file for automatic input to the CHS or NOAA computer routines, but this is simply a matter of data formatting and was not a function of the technique being demonstrated. Finally, the CHS typically requires 60 days of data for a harmonic analysis, and the NOAA prefers 30 days for simultaneous observations. Therefore the GPS buoy did not meet this need. Extending the time of observation requires more attention to the power requirements. This may include reconfiguration of the electronics on the buoy. For future projects, consideration should be given to expanding the GPS sampling intervals to two or three seconds, and to logging the GPS data on the buoy. This would include transmission to the buoy, computation of the antenna heights in real-time, and saving only the ASCII solution files and not the much larger binary raw data files. This would require less power because a receiving radio does not use as much power as a transmitting radio (about 30 percent less for the radios used on this project).

6.3 Third Project Objective

The third objective, a datum recovery, was demonstrated by running spirit levels to the GPS reference station from the local tidal benchmarks, and by assigning a known value for chart datum to the reference station. The results from the GPS buoy were then

on the chart datum. The resulting GPS based mean tide height was within 1 mm of the mean tide height from the Saint John permanent gauge, and within 9 mm of the Socomar gauge.

6.4 Conclusions

The concept of using GPS observations from a floating platform was successfully introduced to both the CHS and NOAA. Each agency actively participated in this project, and have subsequently begun efforts to use OTF GPS techniques in their datum determination and nautical charting programs.

The GPS results are within the range of results from the Saint John permanent gauge and the Socomar gauge installed by the CHS for this project. In fact, on a sample by sample basis, the data from the GPS and Socomar pressure gauge correspond better than either compared to the Saint John permanent gauge. The spectrum of the differences between each pair of gauges reveals tidal frequencies in each case, except between the GPS and Socomar pressure gauge. This indicates that the Saint John permanent gauge contains tidal driven height errors. The maximum height differences also occur during half tide level, when the current velocity would be expected to be a maximum. Therefore, I believe the Saint John permanent gauge has a lag in the height of the water surface inside the well as compared to the actual river surface outside the well.

A height difference was also detected between the water surface and the ellipsoid in the Saint John Harbour. This relationship can be applied to future GPS surveys in the area to reduce the observations to the chart datum.

6.5 Recommendations for Future Projects

A prime consideration for the implementation of the "GPS buoy" concept is the use of a buoy that is already in service along a fairway or channel. If this is possible, then the cost of the platform will be minimized. Further, if the Coast Guard can place, and/or service, the buoy as a part of their normal maintenance process, then another major cost can be minimized.

The choice and arrangement of equipment dictate the power consumption of the total system. This aspect must be carefully designed to provide the desired duration of data. Consideration should be given to the measurement of pitch and roll and real-time data transmission versus data storage on the buoy. Both of these factors will play a major role in reducing power consumption, cost, and complexity of the system. If pitch and roll measurements are required, then it may be possible to use a smaller, less accurate sensor, that requires less power. The disadvantage is a loss in accuracy of the measurements (see Figure 3.3).

Consideration should also be given to the optimal use of the original data series. During this project, the 1 Hz series was reduced to a 15 minute series for comparison with the other gauges. A filter was used to remove heave effects (equation 4.3). It is possible to use the entire data set to compute the spectrum of both the tidal constituents and the buoy motion. This may also reveal other phenomena not seen with existing gauging techniques.

To fully realize the potential of the GPS for precise water surface measurements requires the creation of a transformation function between the water surface and the

ellipsoid. This would allow a user of OTF GPS to reduce their instantaneous height to a chart datum throughout the geographic extent of the transformation parameters.

It is hoped that this work will help lead the way to the realization of practical techniques to refine the characteristics of the tide. The net result is increased accuracies of datum determination, hence more accurate navigation charts and marine engineering projects.

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Appendix A

Rayleigh Criterion for Separation of the Major Constituents

Appendix A

	Sa	Ssa	Mm	Mf	MSf	K1	O1	P1	M2	S2	N2	K2	L2	T2	M4
Ssa	365														
Mm	29.8	32.4													
Mf	14.2	14.8	27.1												
MSf	15.4	16.1	31.8	182.5											
K1	1	1	1	1.1	1.1										
O1	1.1	1.1	1.1	1.2	1.2	13.7									
P1	1	1	1	1.1	1.1	182.7	14.8								
M2	0.5	0.5	0.5	0.5	0.5	1.1	1	1.1							
S2	0.5	0.5	0.5	0.5	0.5	1	0.9	1	14.8						
N2	0.5	0.5	0.5	0.5	0.5	1.1	1	1.1	27.6	9.6					
K2	0.5	0.5	0.5	0.5	0.5	1	0.9	1	13.7	182.9	9.1				
L2	0.5	0.5	0.5	0.5	0.5	1	1	1	27.5	31.8	13.8	27.1			
T2	0.5	0.5	0.5	0.5	0.5	1	0.9	1	15.4	364.1	9.9	121.9	34.8		
M4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	
MS4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	14.8

Rayleigh Criterion (in days) for the separation of the major tidal harmonic constituents. Computations are based on the angular speed of each constituent as given in Forrester, 1983.

$$T(\text{days}) = [\,360^\circ / (\text{speed}_1(^\circ/\text{hr}) - \text{speed}_2(^\circ/\text{hr}))] / 24(\text{hr/day})$$

Appendix B

October 29, 993 Meeting Attendees

Appendix B

October 29, 1993, Meeting at Bedford Institute

The first meeting to discuss the GPS Tides project occurred at the Bedford Institute of Oceanography, Bedford, Nova Scotia on 29 October, 1993. The following individuals were present:

Canadian Hydrographic Service	Bob Burke Reg Lewis Pete McGinn Charlie O'Reilly
Canadian Coast Guard	Joe LeClair
Public Works Canada	Jean-Claude Vautour
University of New Brunswick	Dave Wells Richard Phelan Steve DeLoach

Appendix C

Plots and Figures

Appendix C

Appendix C contains a series of plots related to Chapter 5, Analysis and Results.

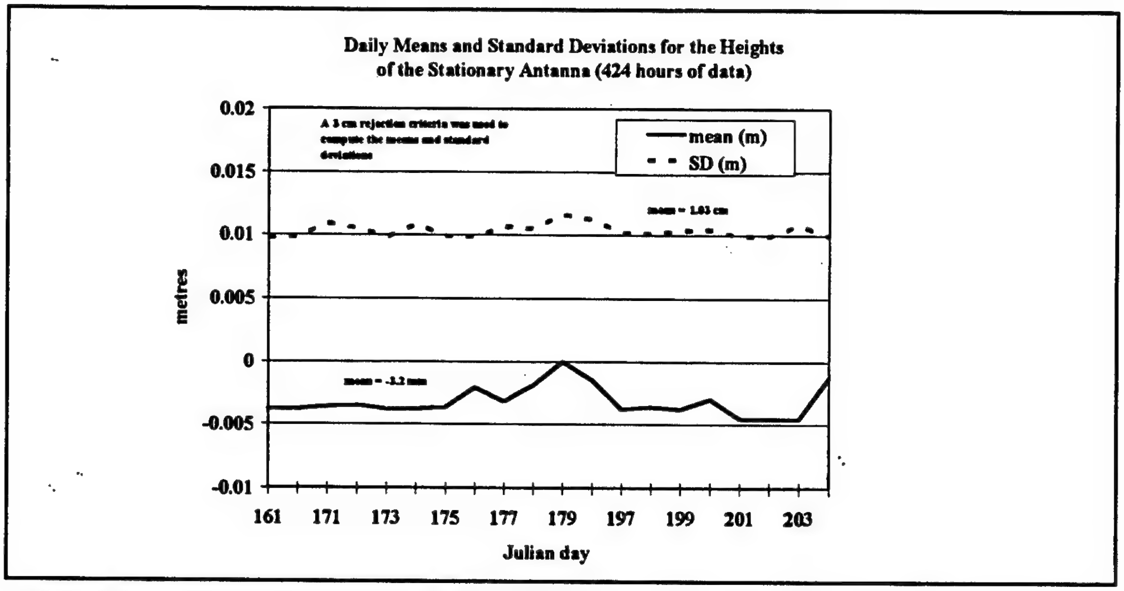

Figure C1 Daily means and standard deviations of the stationary antenna, mounted on the roof of the Coast Guard's administration building.

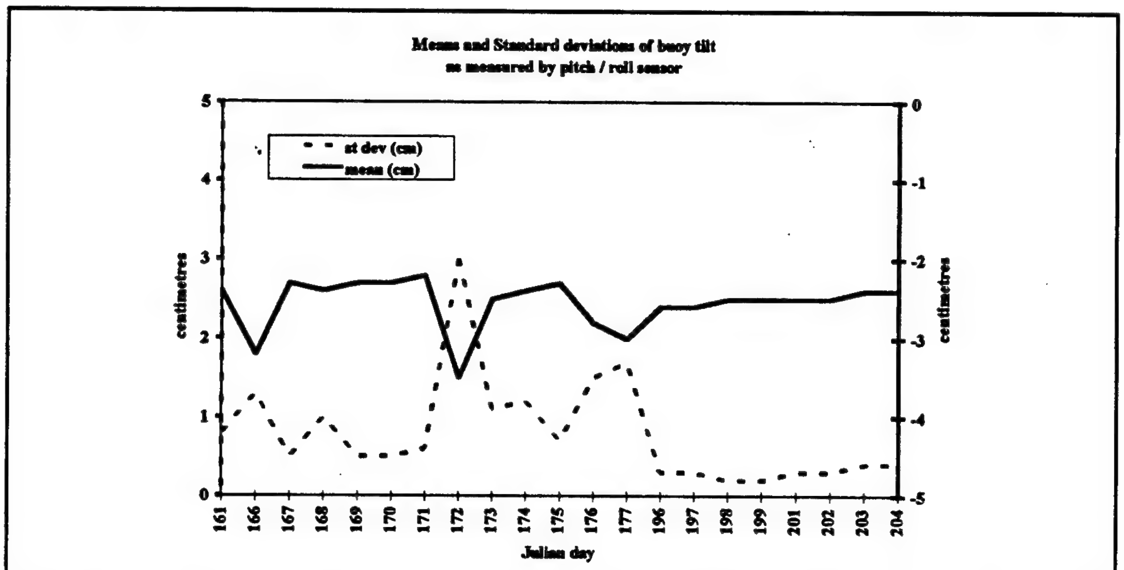

Figure C2 Means and Standard deviations of the buoy tilt (pitch and roll). Values converted to height in centimetres, from angular measure.

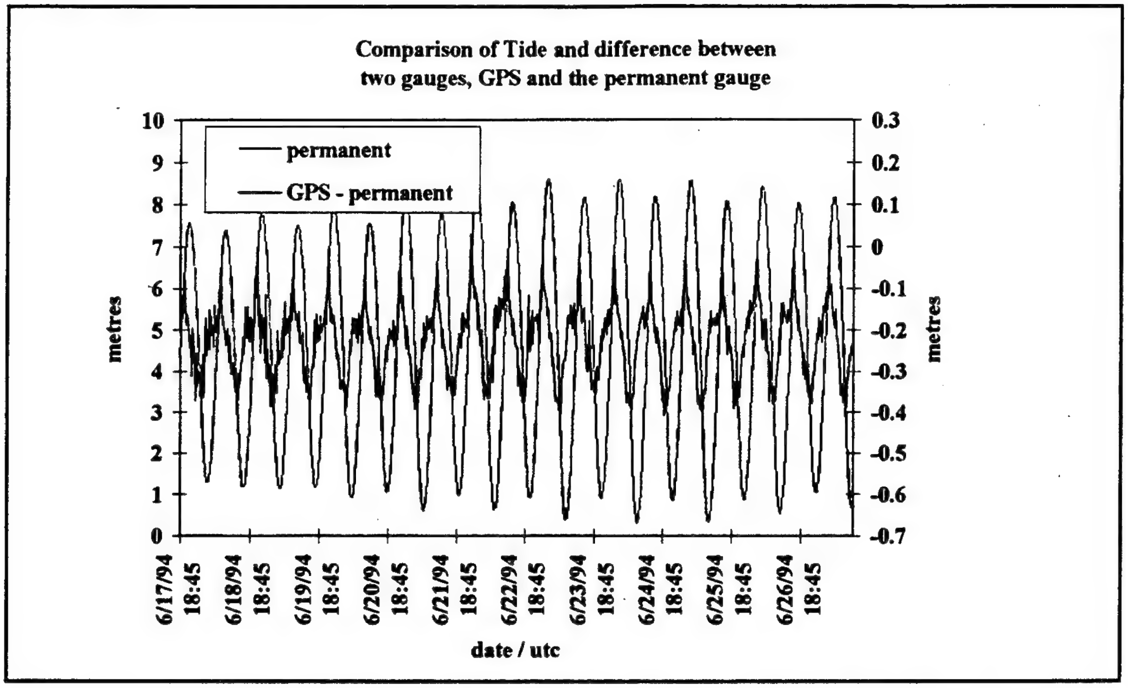

Figure C3 The residuals (difference between the GPS Buoy and permanent gauge) plotted against the tide height, during the offshore data collection.

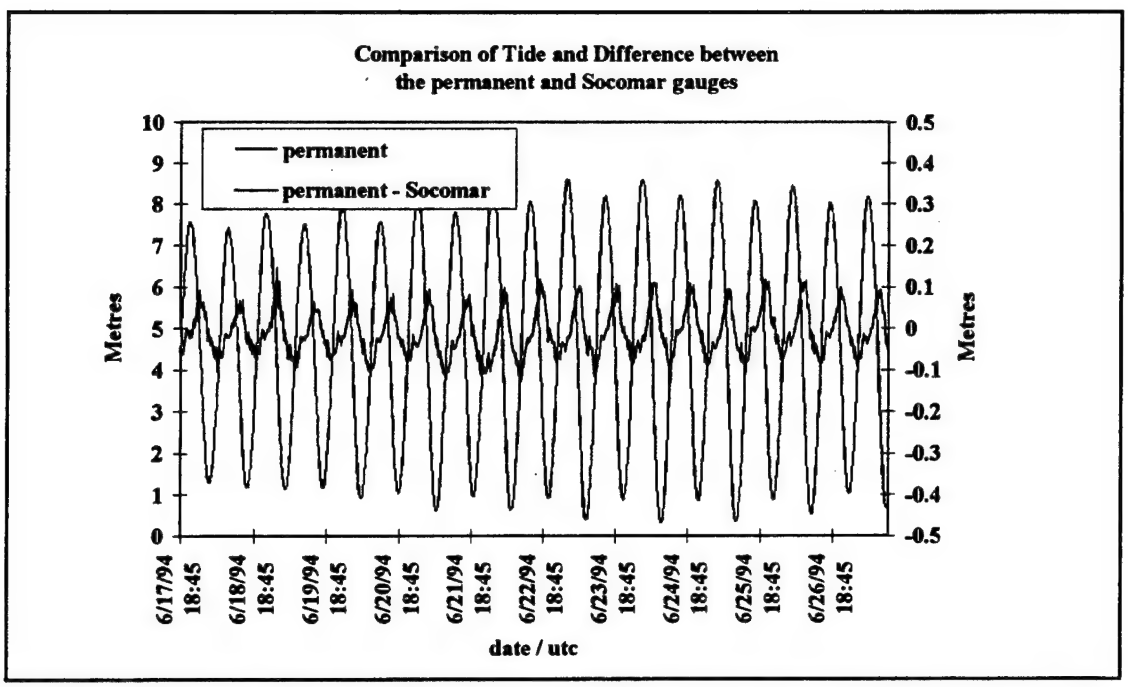

Figure C4 The residuals (difference between the permanent and Socomar gauges) plotted against the tide height, during the offshore data collection.

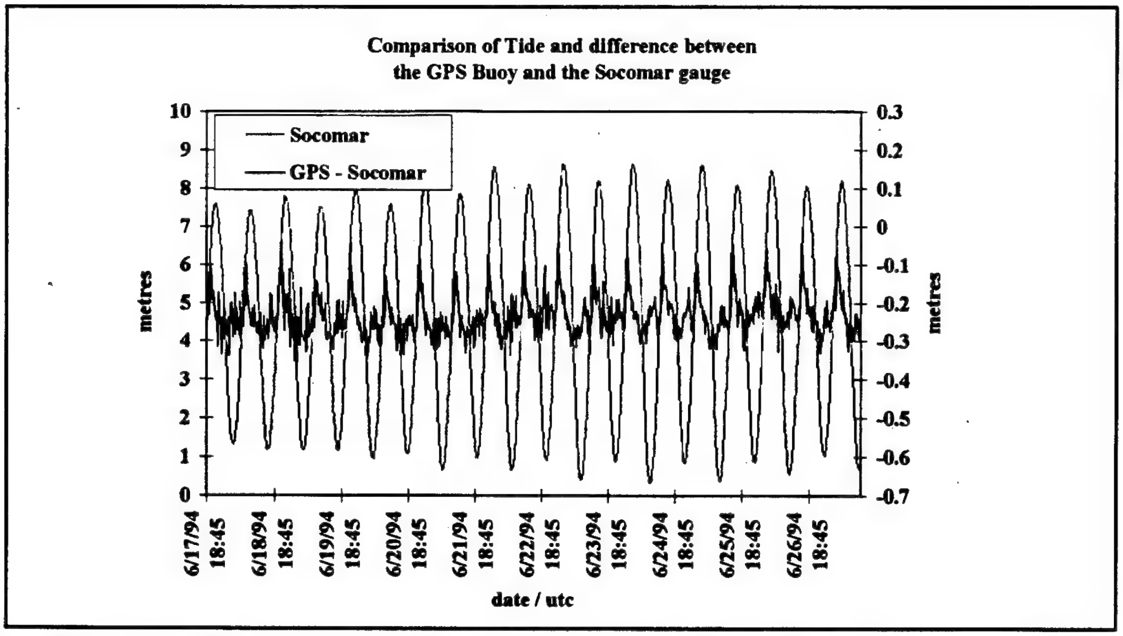

Figure C5 The residuals (difference between the GPS Buoy and Socomar gauge) plotted against the tide height, during the offshore data collection.

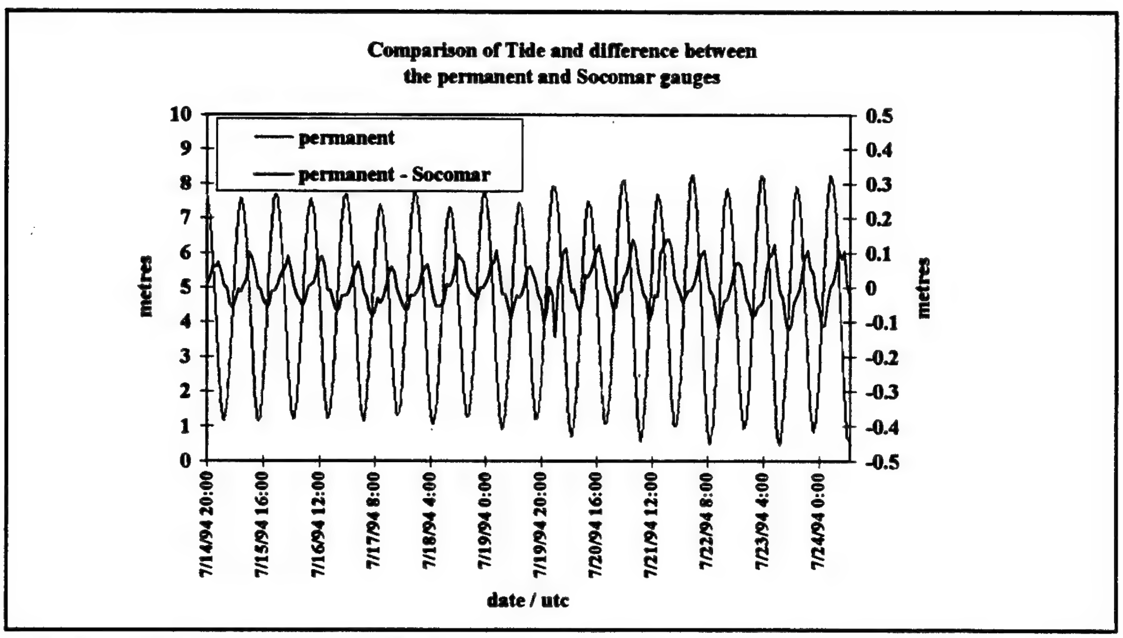

Figure C6 The residuals (difference between the permanent and Socomar gauges) plotted against the tide height, during the inshore data collection.

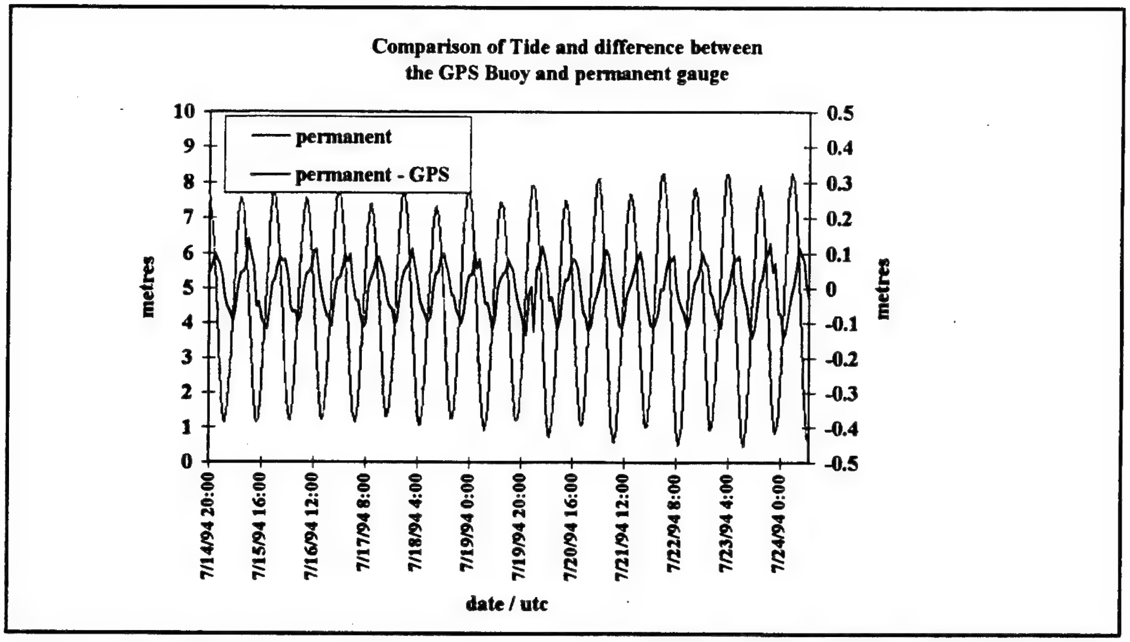

Figure C7 The residuals (difference between the GPS Buoy and the permanent gauge) plotted against the tide height, during the inshore data collection.

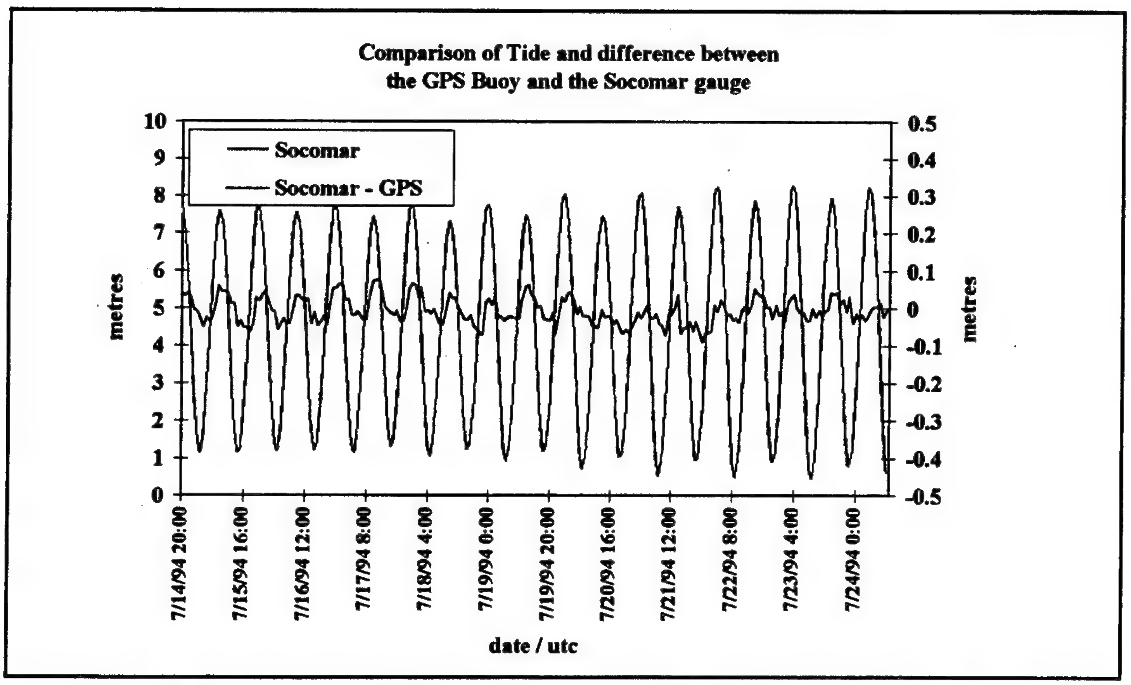

Figure C8 The residuals (difference between the GPS Buoy and Socomar gauge) plotted against the tide height, during the inshore data collection.

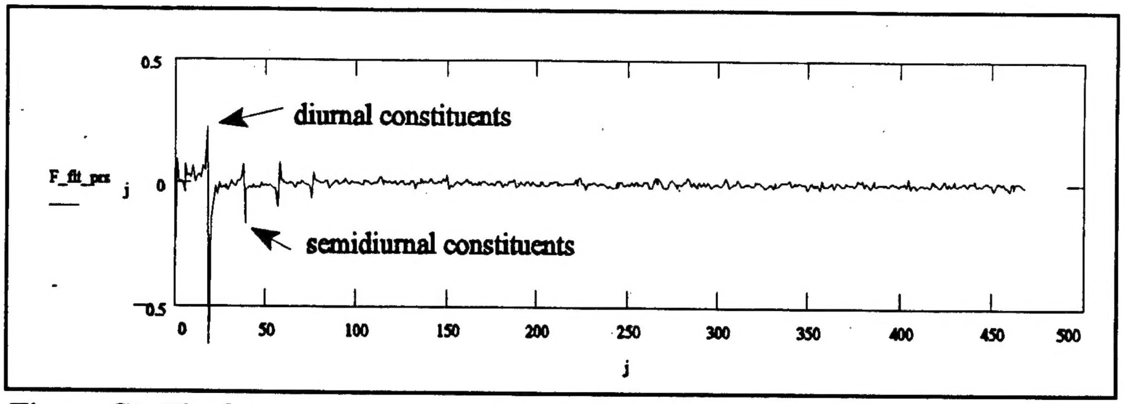

Figure C9 The frequency spectrum of the residuals between the permanent (flt) and the Socomar (prs) gauges. The period of the constituent is found by 1 / (j / # samples).

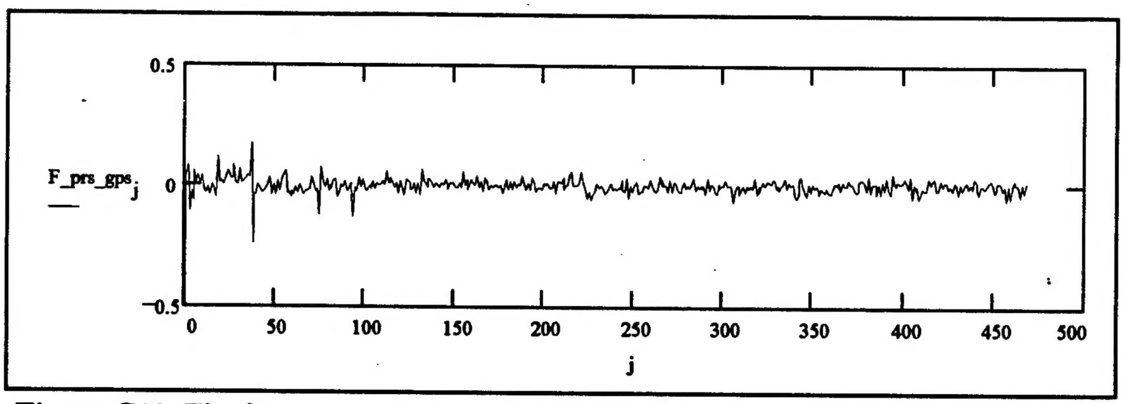

Figure C10 The frequency spectrum of the residuals between the GPS Buoy (gps) and the Socomar gauge (prs). The semidiurnal constituent is beginning to appear from the noise.

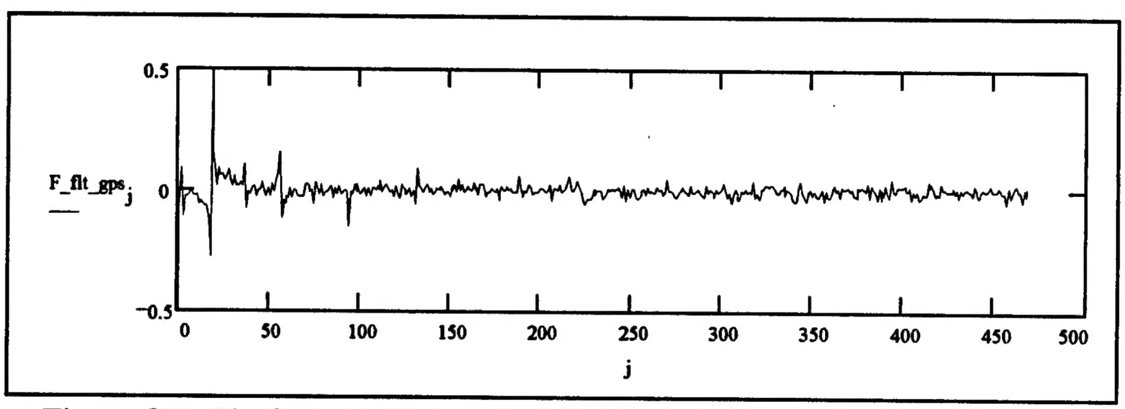

Figure C11 The frequency spectrum of the residuals between the GPS Buoy (gps) and the permanent gauge (flt). The diurnal constituents are easily visible.

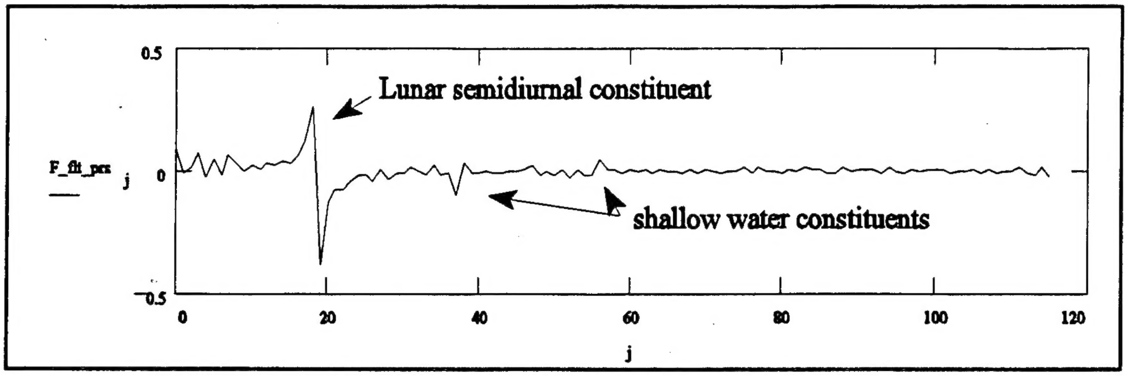

Figure C12 The frequency spectrum of the residuals between the permanent (flt) and Socomar (prs) gauges. The semidiurnal and shallow water constituents are visible.

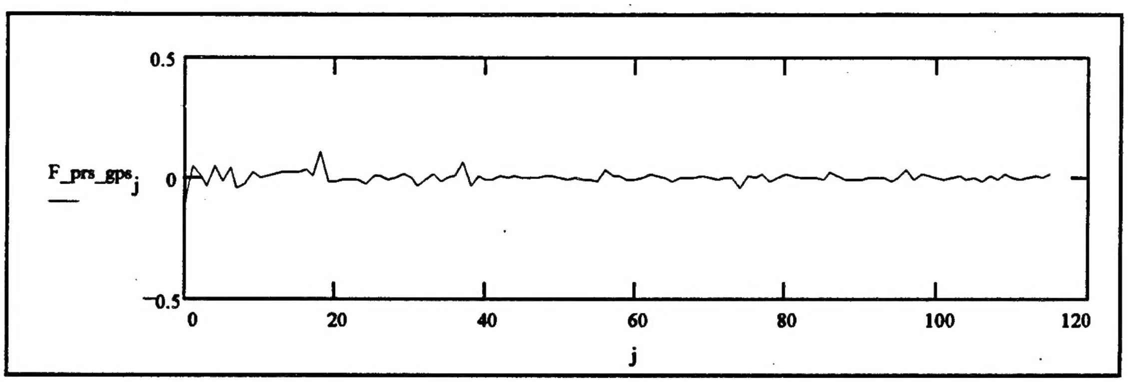

Figure C13 The frequency spectrum of the residuals between the GPS Buoy (gps) and the Socomar gauge (prs). The tidal constituents are not strong compared to the noise in the spectrum.

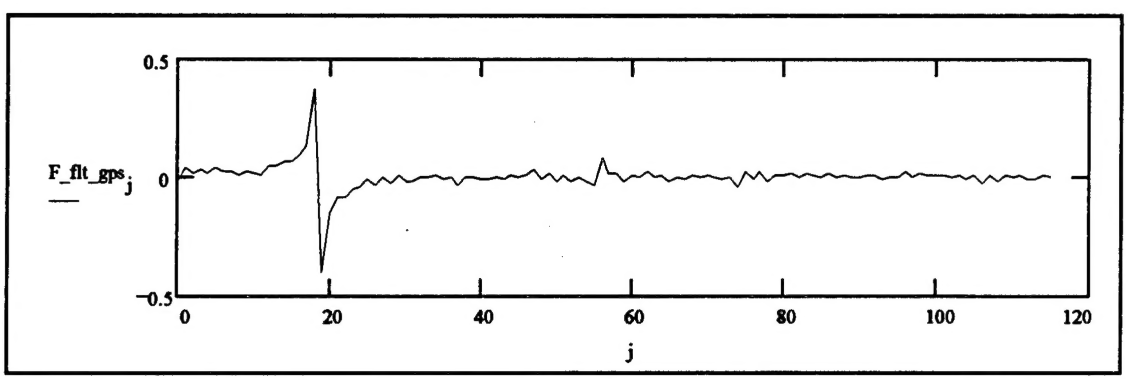

Figure C14 Thefrequency spectrum of the residuals between the GPS Buoy (gps) and the permanent gauge (flt). The Lunar semidiurnal and shallow water constituents are again strongly visible in the record.

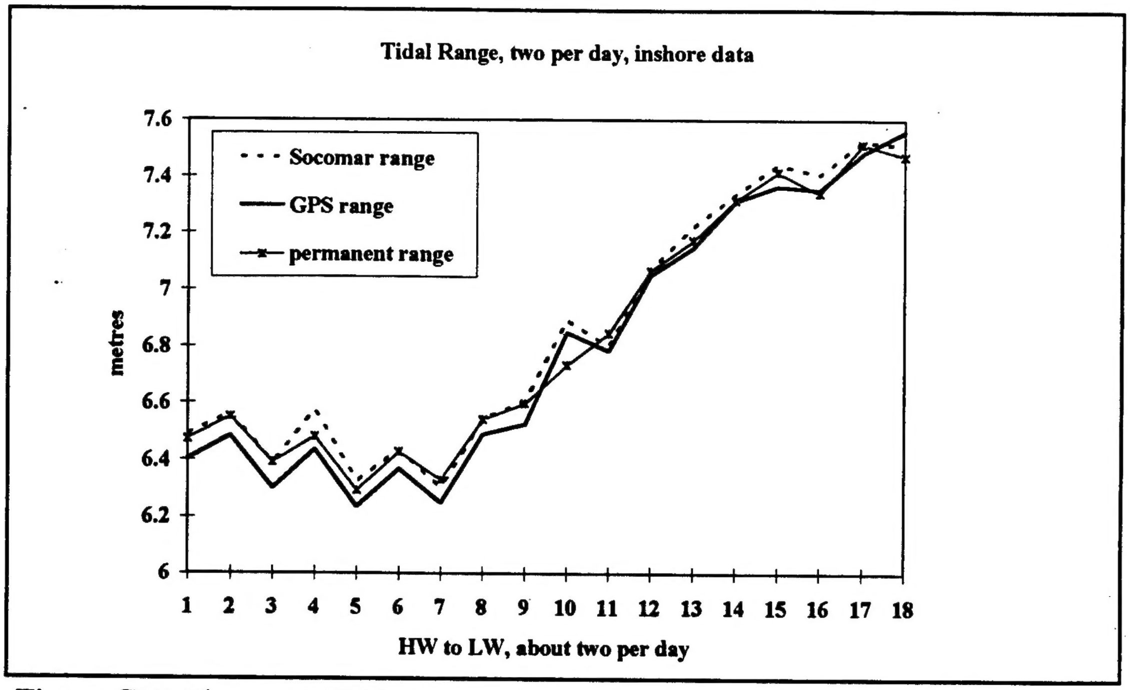

Figure C15 The range of tide from each gauge (permanent, Socomar, and GPS Buoy), during the inshore data collection.

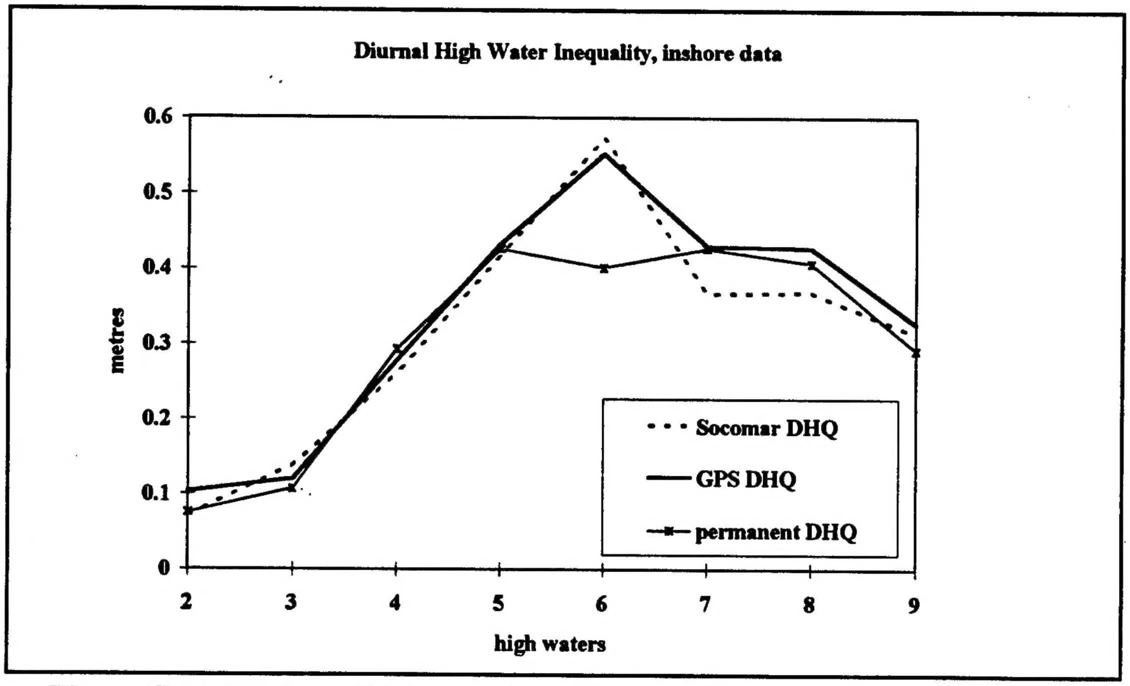

Figure C16 The diurnal high water inequality (DHQ) from each gauge (Socomar, permanent and GPS Buoy) during the inshore data collection.

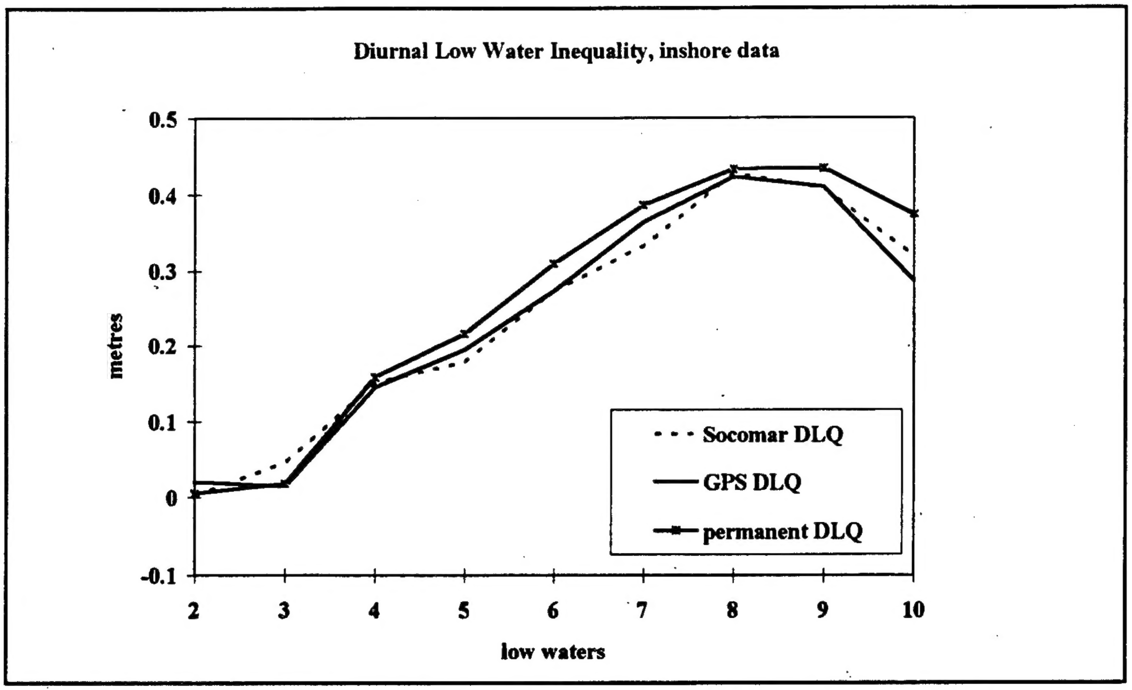

Figure C17 The diurnal low water inequality (DLQ) from each gauge (Socomar, permanent and GPS Buoy) during the inshore data collection.